Experimental results and studies on the (HL-)LHC LRBB compensation

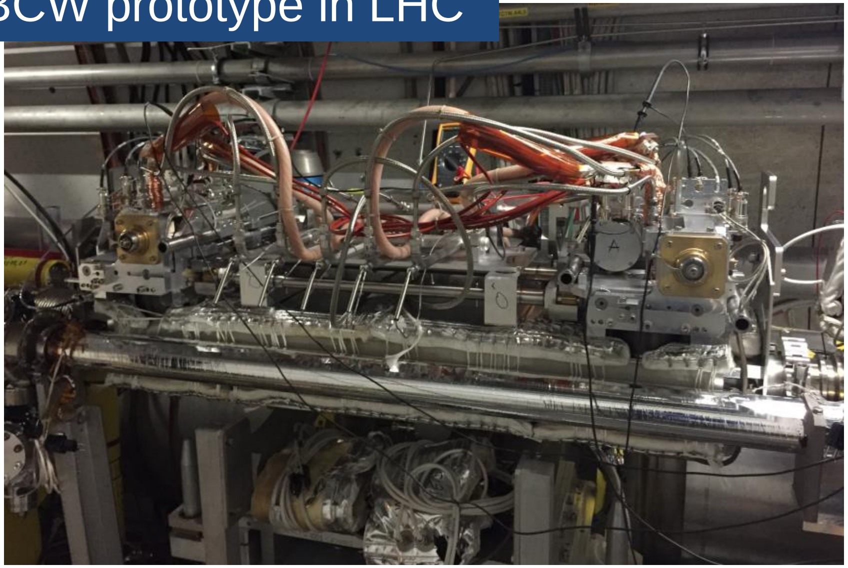
D. Pellegrini, A. Poyet, K. Skoufaris and G. Sterbini, with fundamental contributions from Y. Papaphilippou, S. Fartoukh and the BBLR compensation MD team.

WG2, 1st September 2017

“On the shoulders” of >20 years of BBC studies

- 1996: V. Shiltsev et al., proposal to use electron beams to compensate BB tune spread in hadron machine
- 2001: J.-P. Koutchouk: proposal to use a DC wire
- 2004: J.-P. Koutchouk, F. Zimmermann, J. Wenninger: SPS wire experiments campaign (lasted >10 year and involving a lot of people)
- 2008: U. Dorda, PhD on wire compensation LHC (F. Zimmermann supervisor)
- 2012: T. Rijoff,MSc on wire compensation for the HL-LHC (F. Zimmermann supervisor)
- 2013: F. Zimmermann and R. Steinhagen: specification for the LHC wire prototypes
- 2015: S. Fartoukh et al.: Compensation of the long-range beam-beam interactions as a path towards new configurations for the high luminosity LHC
- 2016: F. Zimmermann and H. Schmickler, Long-range beam–beam compensation using wires
- **Synergic efforts of Collimation Team, BE-BI, EN-STI, EN-MME,TE-EPC…to transform an idea in HW!**

From the idea to the BBCW prototype in LHC



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Outline

- Experimental results in MD1
- Numerical results from the RDT
- Tracking results for LHC and HL-LHC
- Conclusions and plans

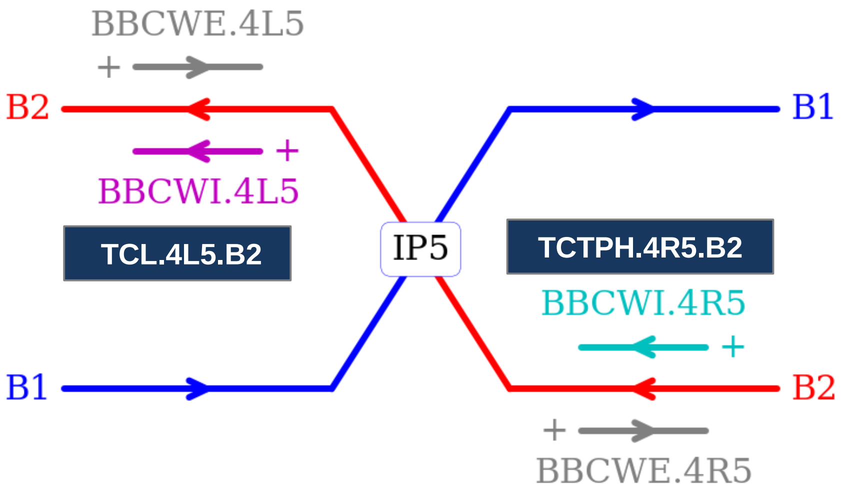
Experimental results of the BBCW MD1

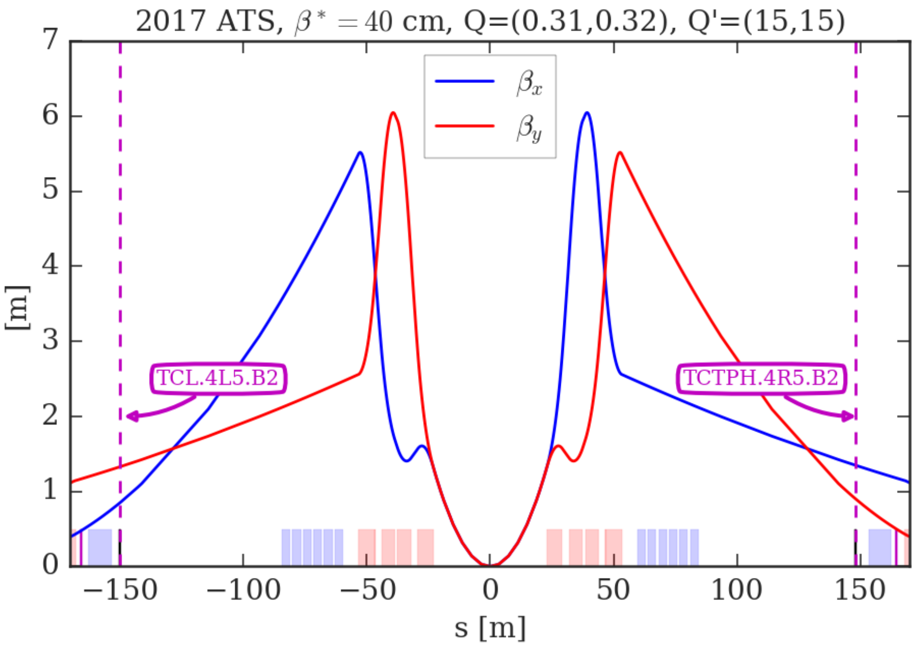
MD2202 team (random order): K. Skoufaris, Y. Papaphilippou, A. Rossi, S. Fartoukh, D. Pellegrini, K. Karastatis, A. Poyet, A. Valishev, S. Kostoglou, G. Sterbini, S. Papadopoulou, M. Fitterer, M. Solfaroli, M. Pojer, M. Hostettler, B. Salvachua, L. Carver, X. Buffat, P. Zisopoulos, H. Bartosik, N. Fuster, S. Redaelli, R. Bruce, M. Gonzales, G. Trad, M. Gasior, C. Zamatzas, J. Olexa, T. Levens, C. Xu, A. Gorzawski, D. Valuch, D. Amorim, I. Lamas Garcia, G. Cattenoz, E. Effinger, L. Poncet, D. Mirarchi, R. Tomas, D. Kaltchev, R. Jones, F. Schmidt…and a many more.

LSWG, 17th August 2017

Introduction

After the installation of the BBCWs (prototypes of the beam-beam wire compensators) during last EYETS and parasitic tests at injections of top energy, an MD took place on the 1st July.





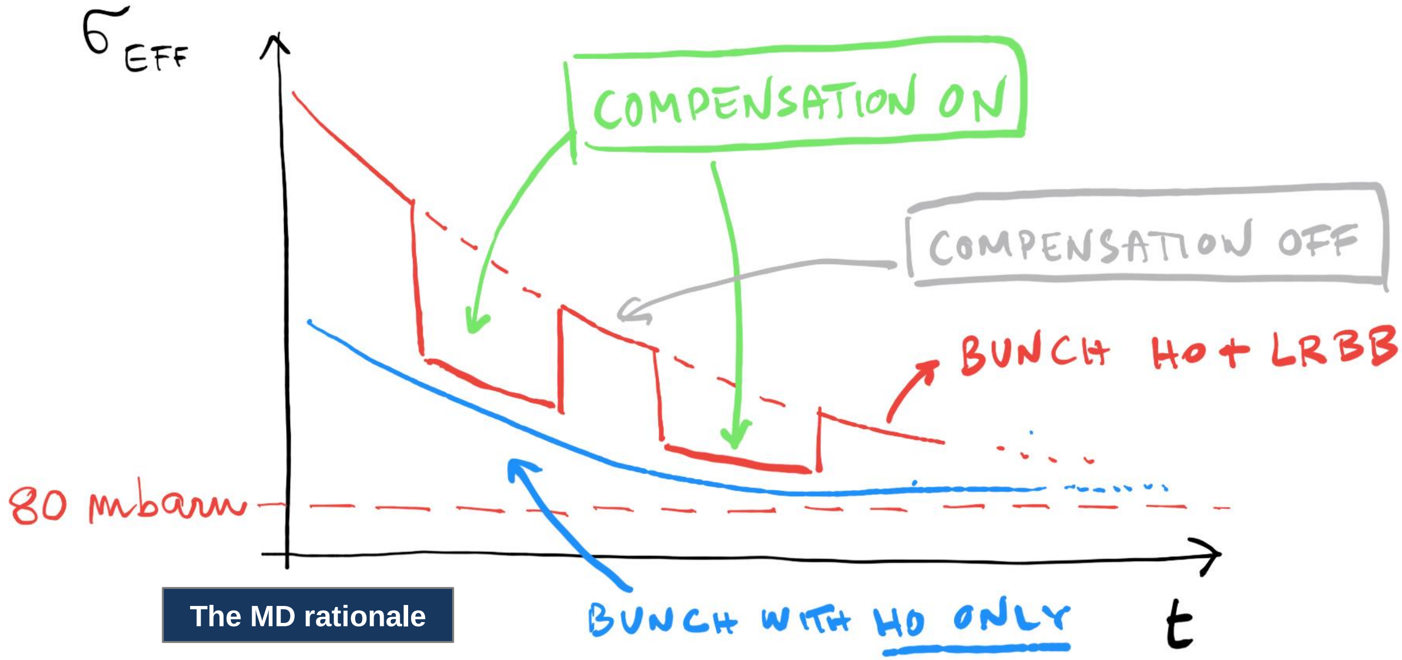
Layout of the BBCW compensation: 2 DC wires in IR5 to compensate the effect of the B1 on the B2 (in IR5).

Objectives of the MD

1. Test with beam the different setting-up procedures (in particular the feedforwards on H-CO and tunes) and observables. Privileged observable: the effective total cross-section of the pp interaction (σ_{EFF})

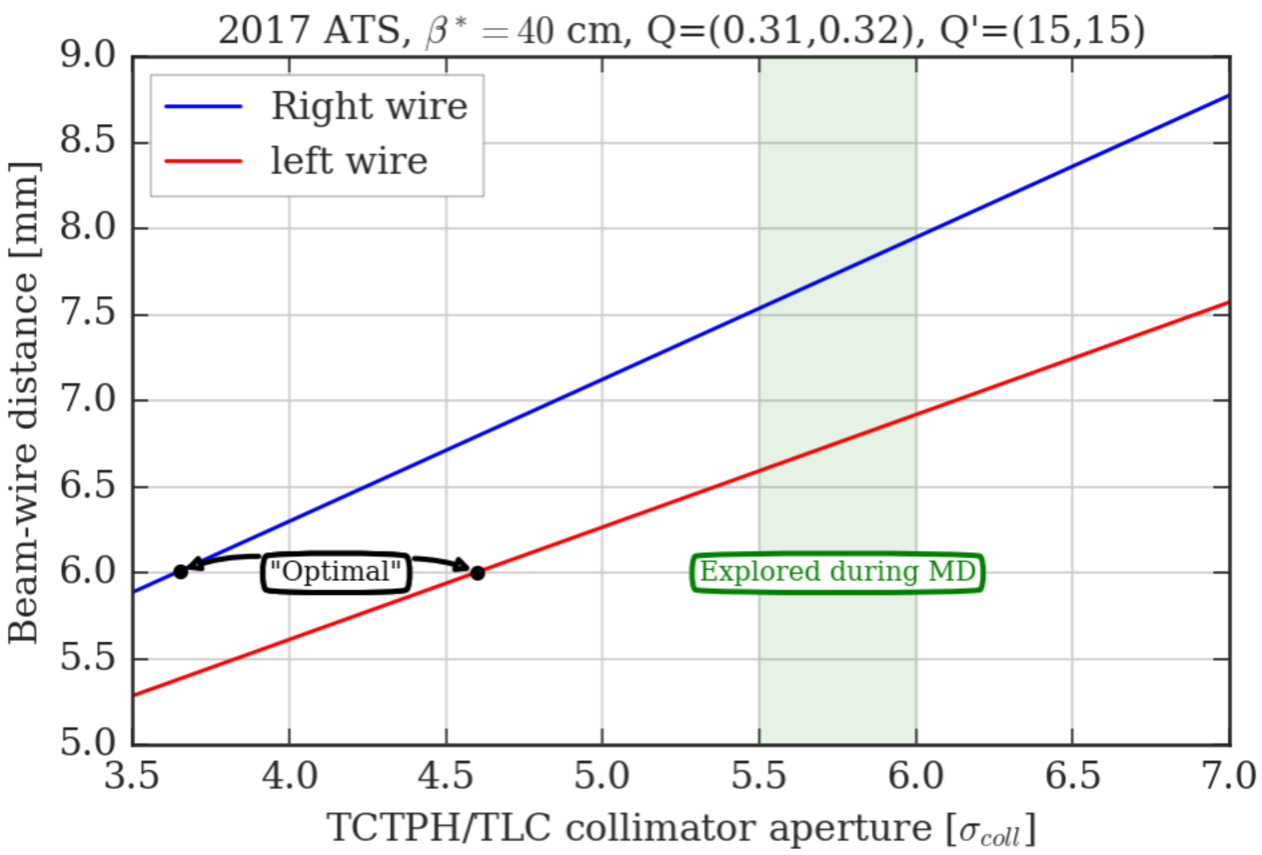
$$\sigma_{EFF} = -\frac{1}{\sum_{IP} L_{IP}} \frac{dN}{dt}$$

1. Find the regime where the BBLR effect is visible.
2. Prove the beneficial effect of the wires.



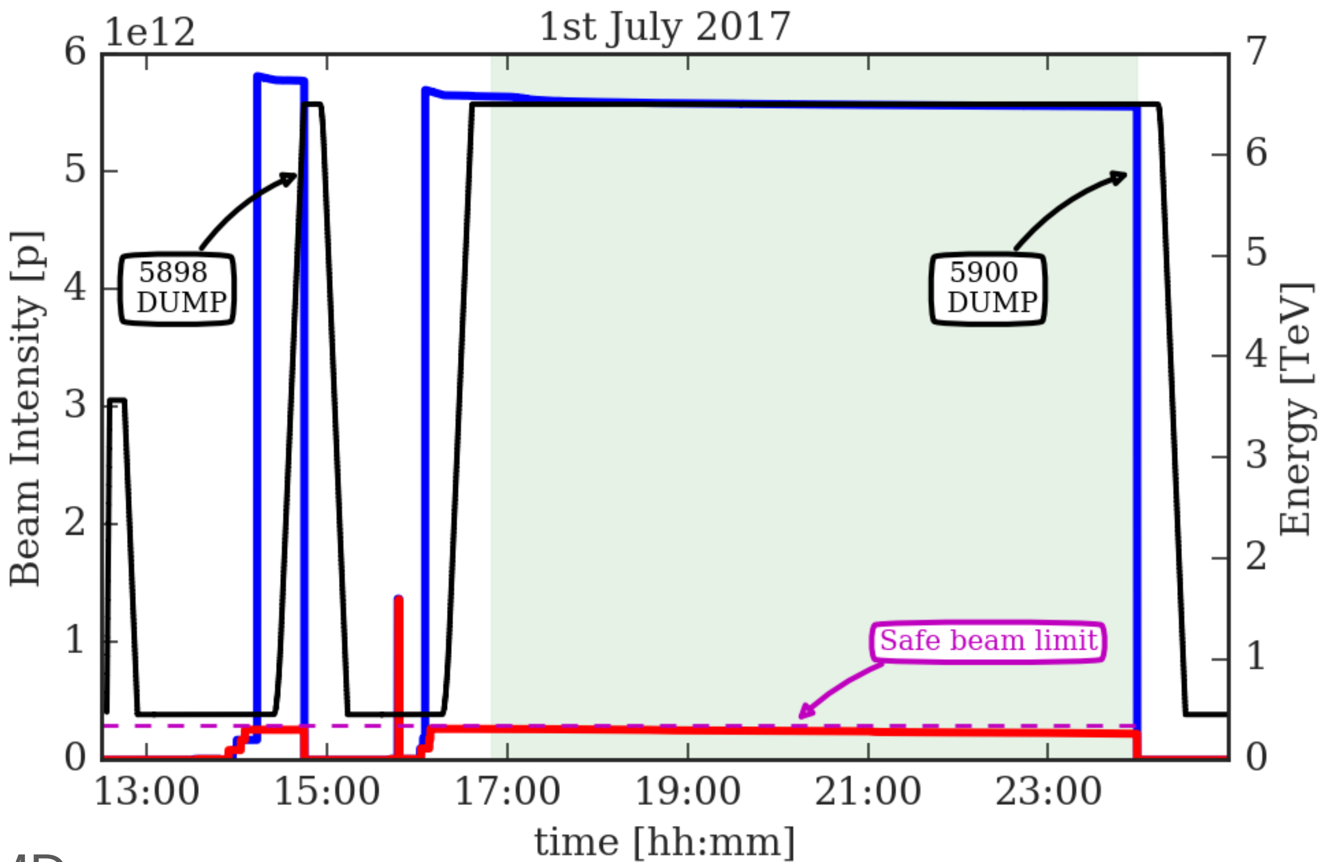
The MD rationale

Constraint for the wire positioning



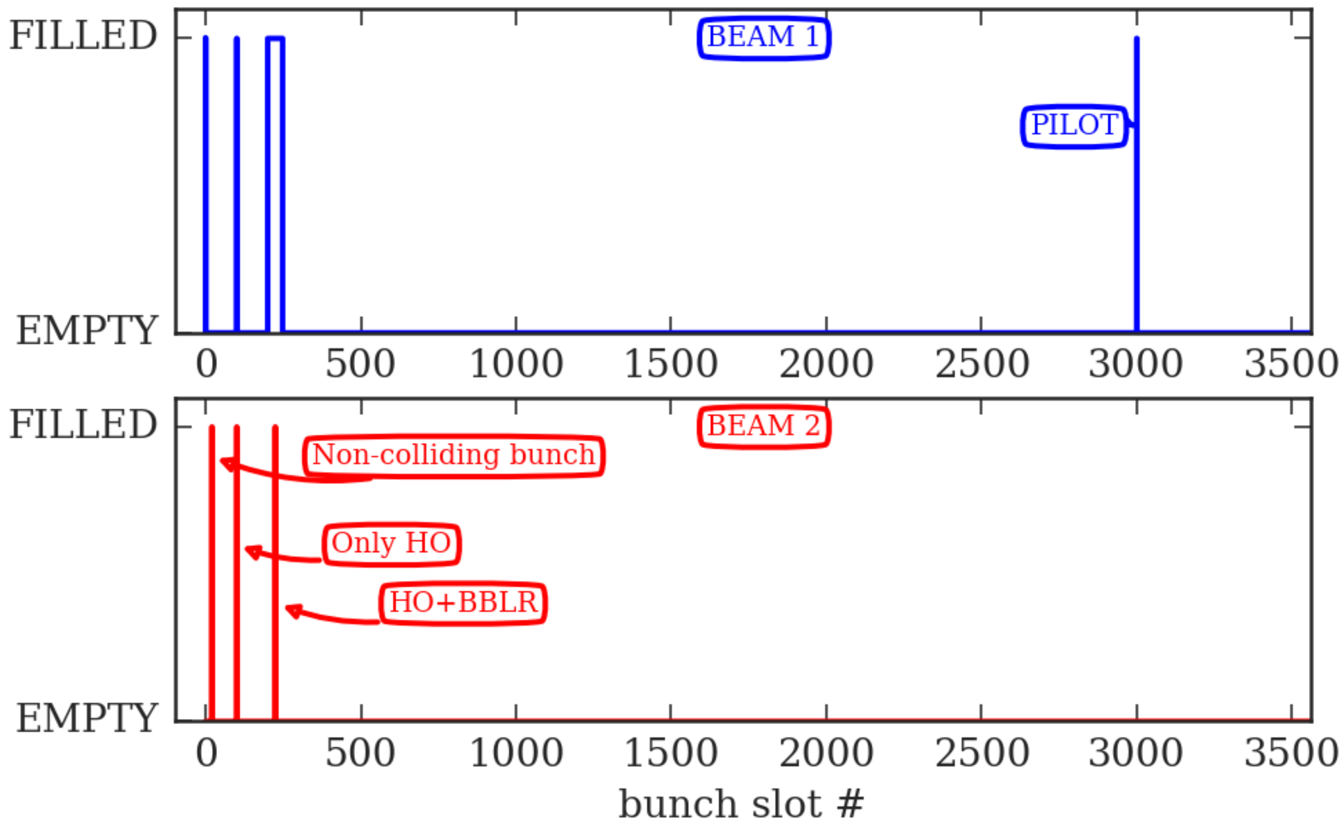
The wires are embedded in tertiary collimators. There are precise limits in the positioning of the wire with respect to the beams. Ideally we would need to put the wires at ~6 mm.

MD2202



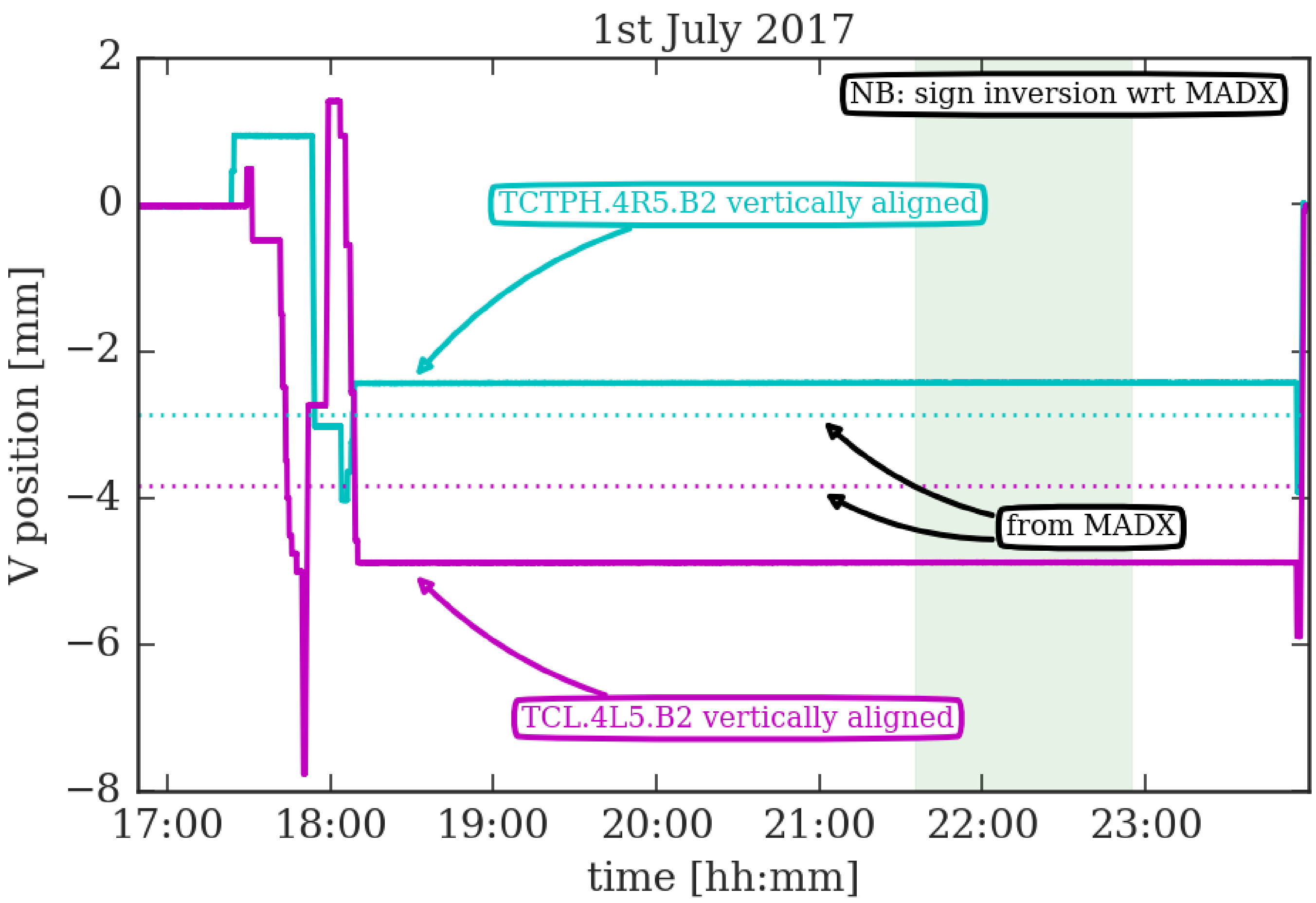
- 10 h MD.
- The FILL5898 was dumped (RF on B1, not clear the reason, RF experts suggest a glitch on the interlock). Half-RF detuning.
- The observations we report concern the FILL5900. Full-RF detuning.

Asymmetric filling scheme



- To approach the wire to the beam the B2 has to be <3e11 p (safe limit).
- We will main concentrate on the two bunches of B2 (Only HO and HO+BBLR).

STEP 1: Alignment of the two wires



Important vertical offset (up to 5 mm) to be corrected with the vertical alignment procedure. This is not a trivial procedure (no V PU).

It would be beneficial to have H+V PUs on the BBCW in HL-LHC.

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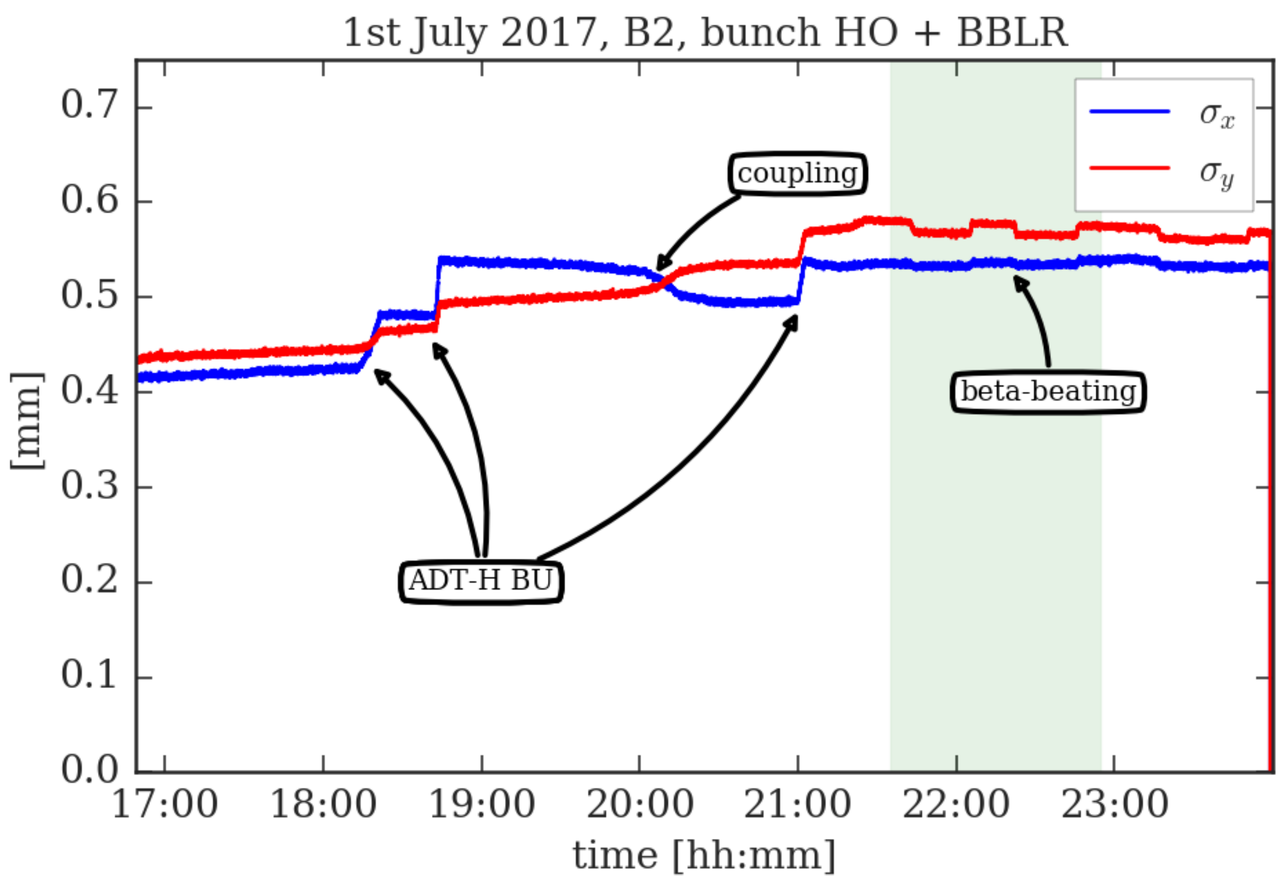
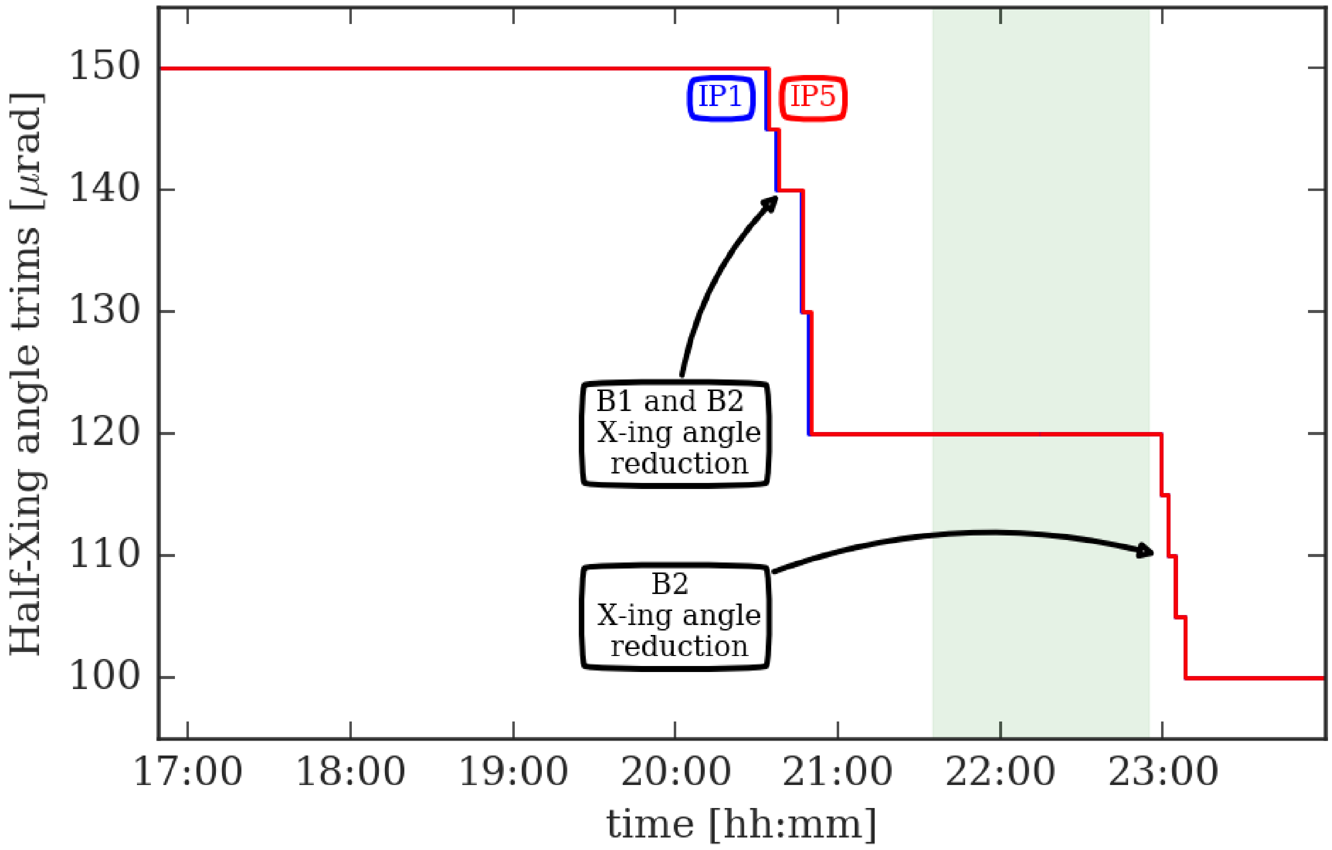
STEP 2: H emittance blow-up



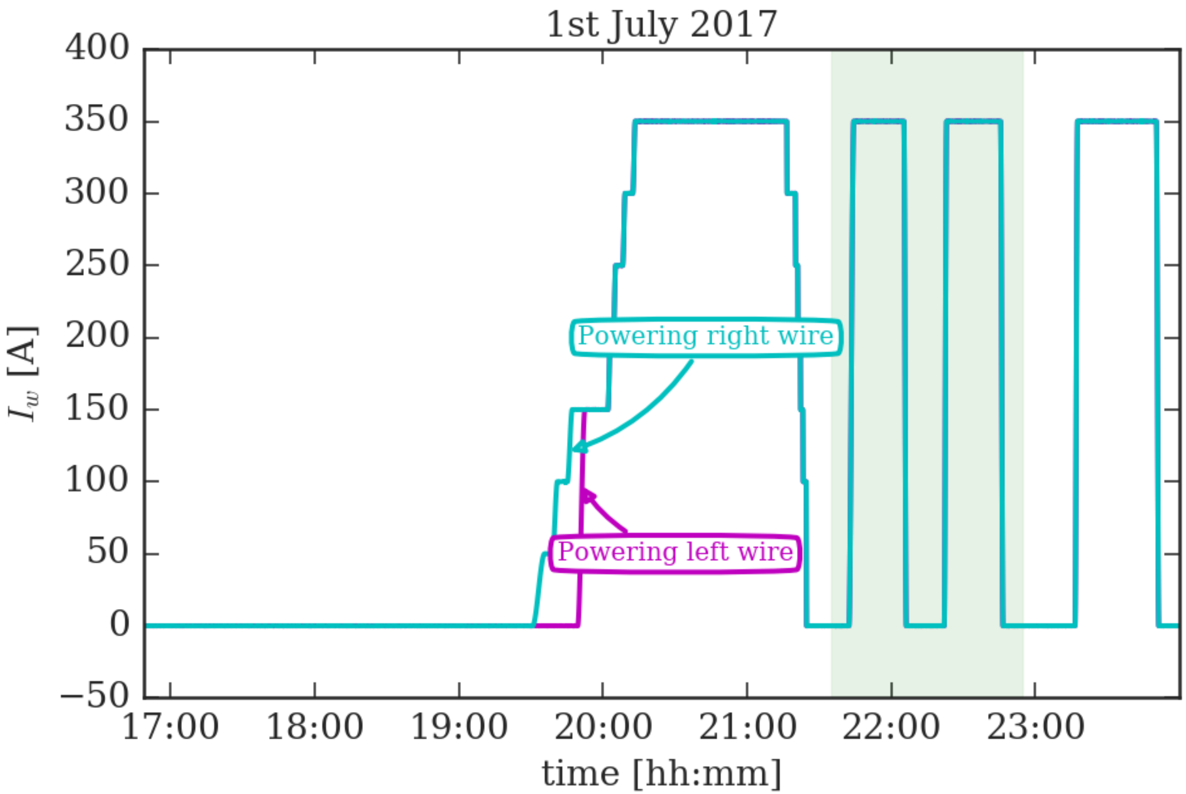
- To increase the LRBB effect the B2 was blown-up to 5-6 mm mrad and the tunes were set to (0.31, 0.32).

STEP 3: Crossing angle reduction



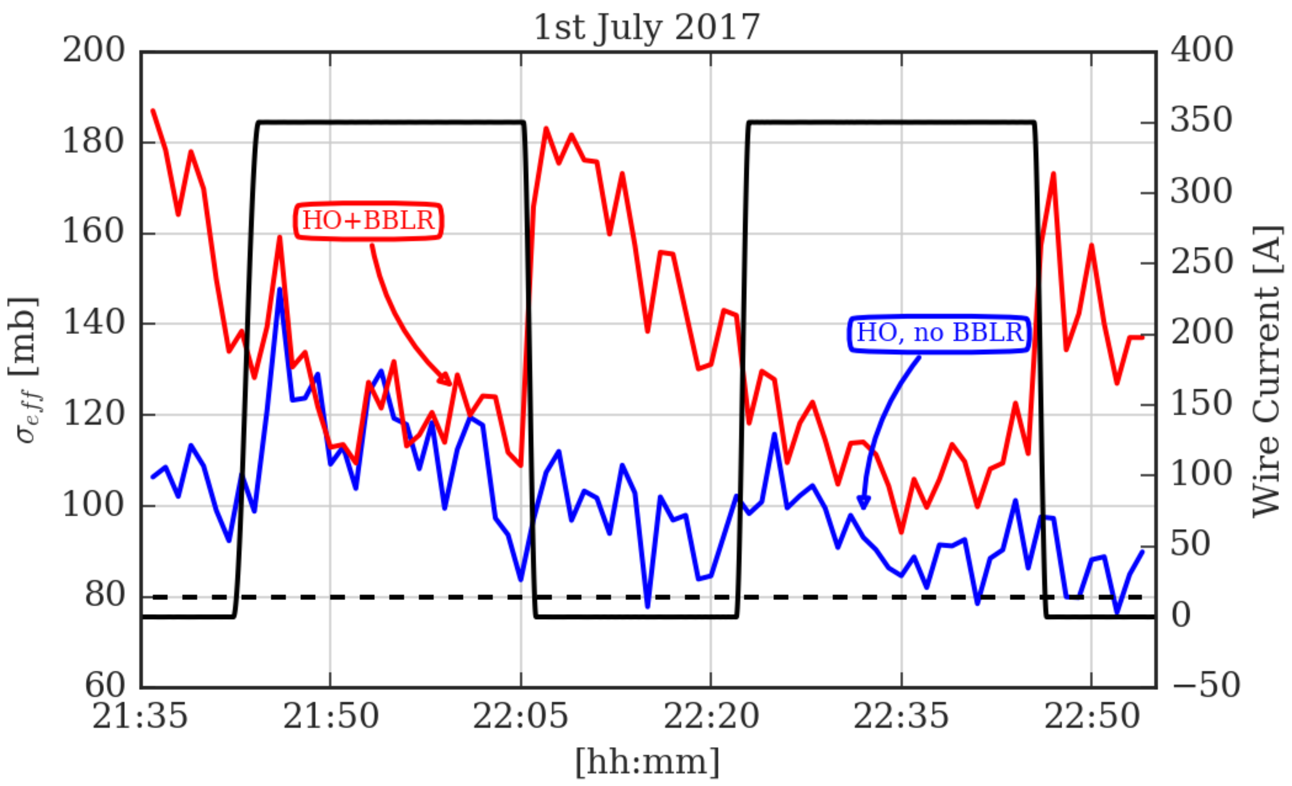
- To increase the BBLR the X-ing angle was reduced. Great synergy with the OP tools developed for the crossing angle anti-leveling.

Finally: powering the wires



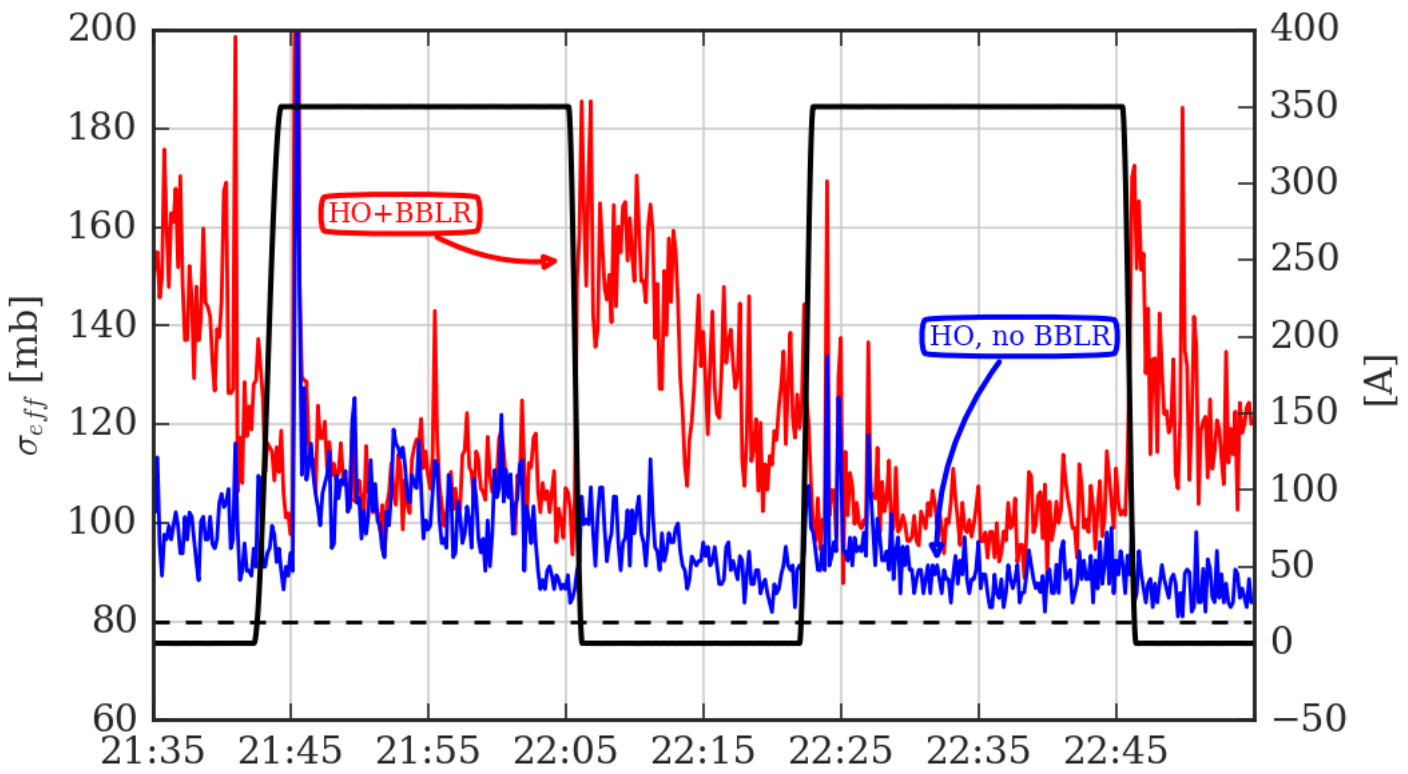
- During the powering of the wires the tunes of the beam (and its position) has to be controlled. The BBCW can move the Q of ~0.01: dipolar and quadrupolar contributions of the wires were compensated with feed-forward trims [backup slides].

Results on the compensation (I)



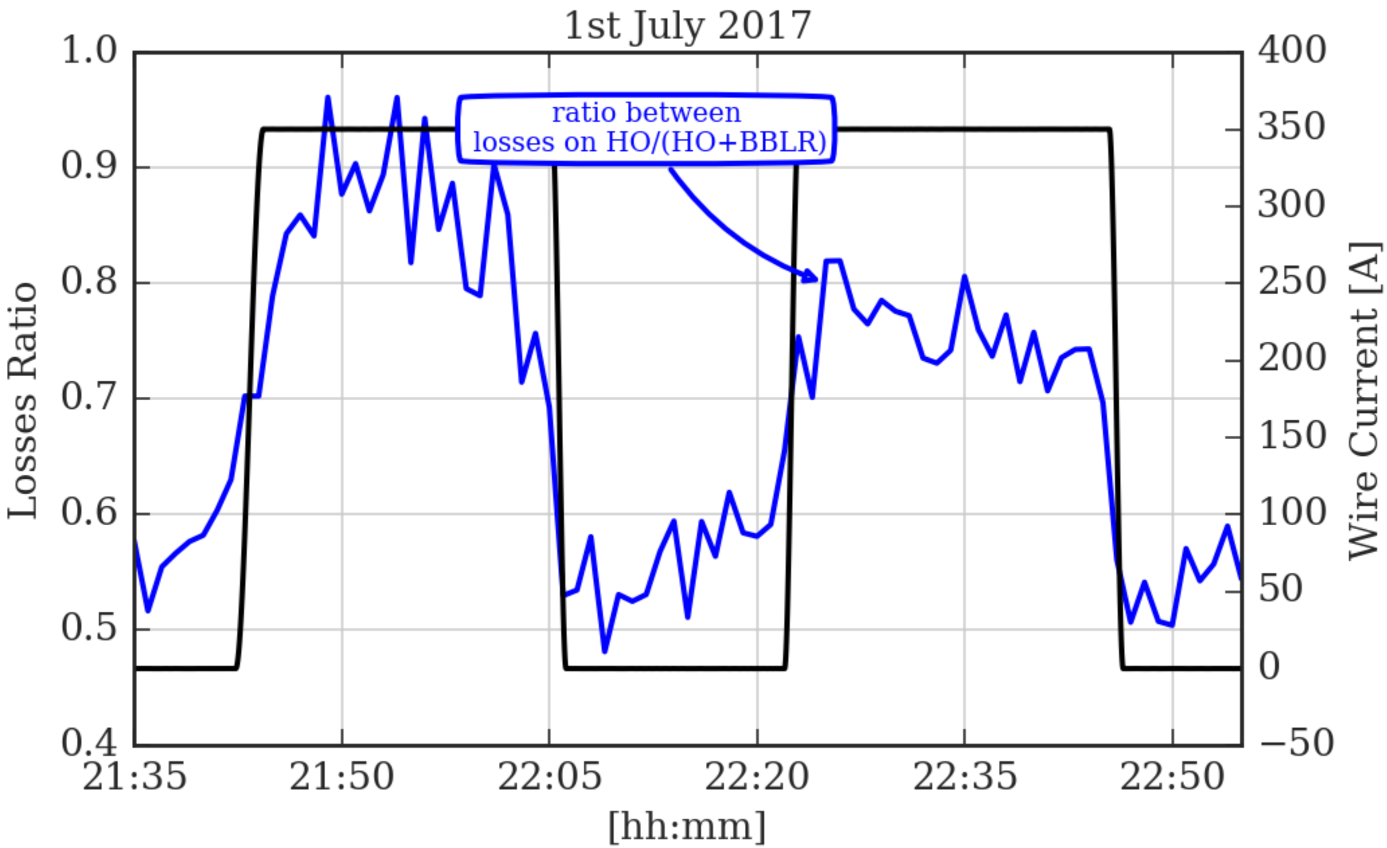
- Compensation seen from the σ_{eff} [credit to N. Karastathis].
- **Clear effect on the BBCW when switching-off: signal compatible with a contraction of the DA.**
- **We need a long integration time (very delicate observable).**

Result on the compensation (II)



- Using dBLM signals to compute the cross-section [credit to A. Poyet].
- **Improved time resolution.**
- **Further checks on calibration needed.**

Result on the compensation (III)



- From the FBCT signals compensation on the losses [credit to M. Hostettler].
- **Clear effect of the BBCW.**

Summary of the experimental results of MD1

- During the MD2202 it was observed for the first time in LHC the effect of a direct compensation of the BBCW. The setting-up procedures were tested and validated.

- The HW (interlock, PCs, jaws temperature/cooling, collimators…) worked smoothly.

- There is a lot of margin of improvement in the procedure: beta-beating/tune feedforward (Luis from Rogelio's team is working on it) and a smoother orchestration of the feedforward trims (Matteo is working on it).

- It is very important to explore the I_w and d_w parameter space and correlate it with the analytical model and the tracking results.

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Numerical results from the RDT

We will use the RDT criterion presented and described in details in

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Compensation of the long-range beam-beam interactions as a path towards new configurations for the high luminosity LHC

Stéphane Fartoukh,[1,*] Alexander Valishev,[2,†] Yannis Papaphilippou,[1] and Dmitry Shatilov[3]

Goal: compensate the BBLR RDTs by using 2 BBCs per IP.

Strong-beam driven RDTs

$$c_{pq}^{\mathrm{LR}} \equiv \sum_{k\in \mathrm{LR}} \frac{\beta_x^{p/2}(s_k)\beta_y^{q/2}(s_k)}{d_{bb}^{p+q}(s_k)}$$

BBCW driven RDTs

$$\begin{cases} c_{pq}^{w.\mathrm{L}} \equiv \boxed{N_{w.\mathrm{L}}} \times \dfrac{(\beta_x^{w.\mathrm{L}})^{p/2}(\beta_y^{w.\mathrm{L}})^{q/2}}{\boxed{(d_{w.\mathrm{L}})}^{p+q}} \\ c_{pq}^{w.\mathrm{R}} \equiv \boxed{N_{w.\mathrm{R}}} \times \dfrac{(\beta_x^{w.\mathrm{R}})^{p/2}(\beta_y^{w.\mathrm{R}})^{q/2}}{\boxed{(d_{w.\mathrm{R}})}^{p+q}}, \end{cases}$$

Assuming

1. the same N_w and d_w for both BBCWs,
2. that the strong beam acts as a DC wire,
3. that the phase advance between BBLRs and BBLRs/BBCW is 0 or 180 deg.

the paper gives **N_w and d_w to compensate 4 RDTs (p1q1, q1p1, p2q2, q2p2) in closed form.**

It is shown as a numerical evidence that by compensating 4 RDTs one can minimize ALL RDTs *if the position of BBCW is conveniently chosen*.

Using the paper's formalism, we will show numerical results on the present LHC (2017 ATS).

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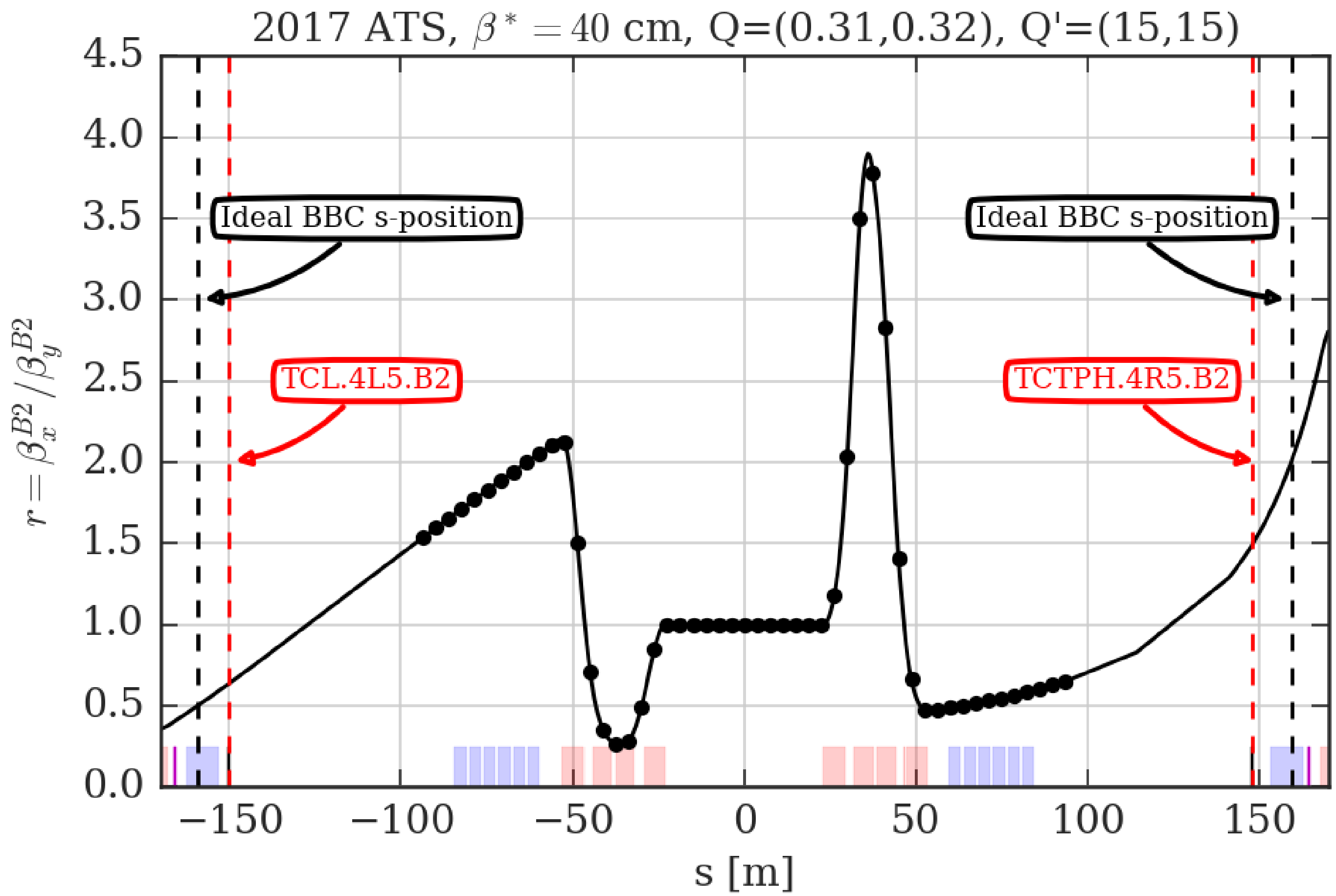
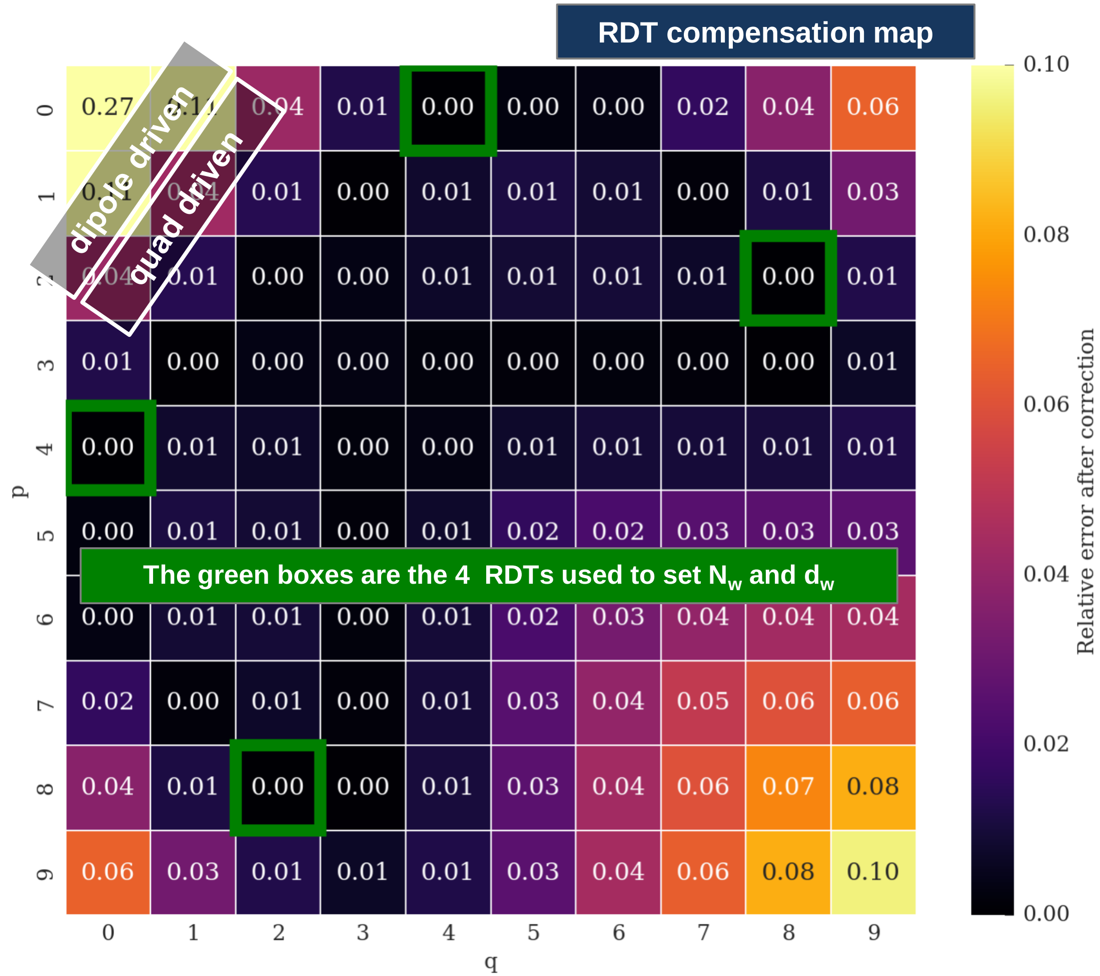
The ideal BBC position in 2017 ATS



The actual position of the BBC is ~10 m apart from the ideal one [backup slides].

We will first consider the ideal case and afterwards the real case per IP5.

IDEAL CASE: 2 BBCW for IP at s_{opt}=+-159 m

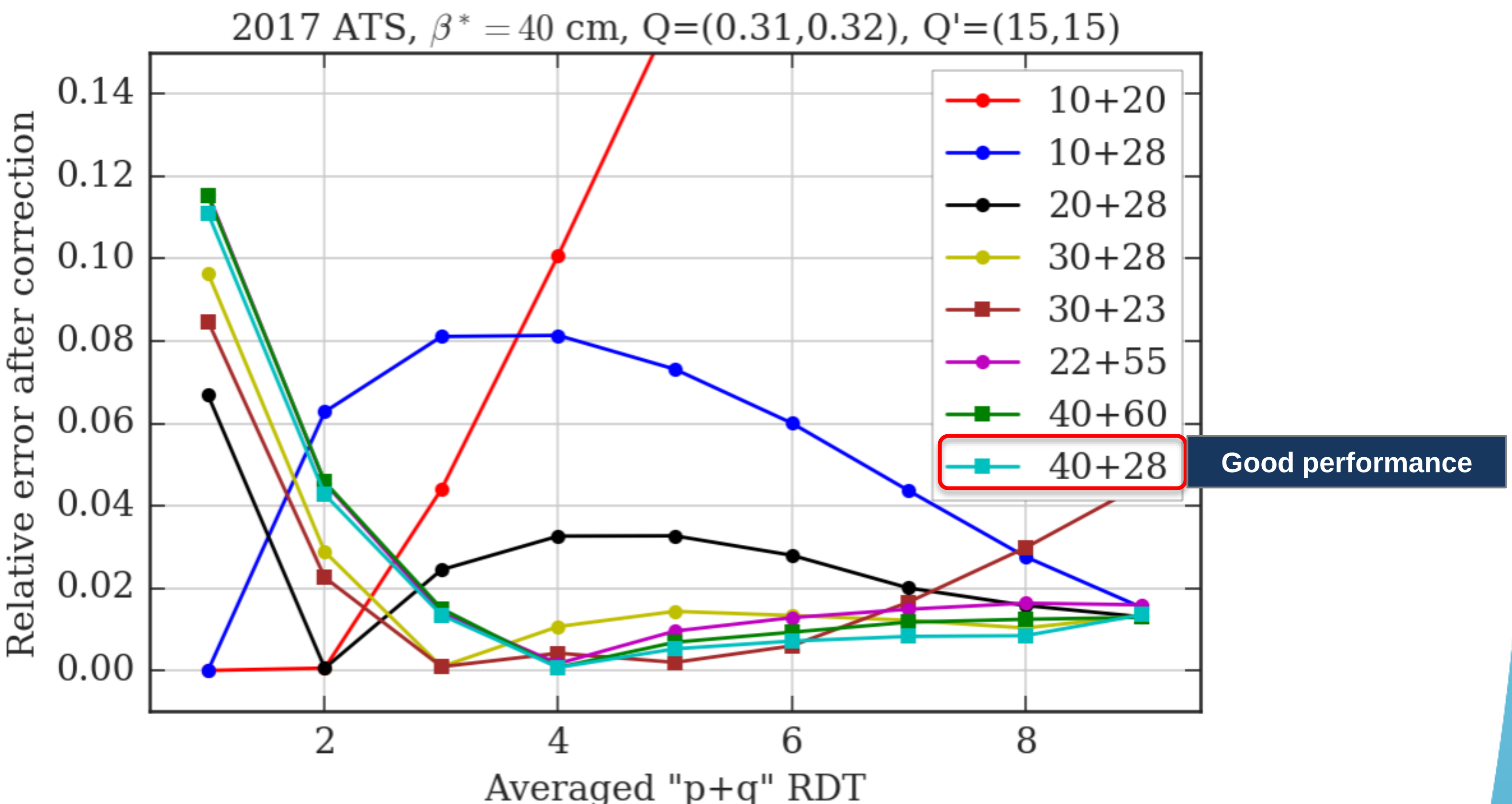


in color code

$$\left| \frac{c_{pq}^{LR} + c_{pq}^{w,L} + c_{pq}^{w,R}}{c_{pq}^{LR}} \right|$$

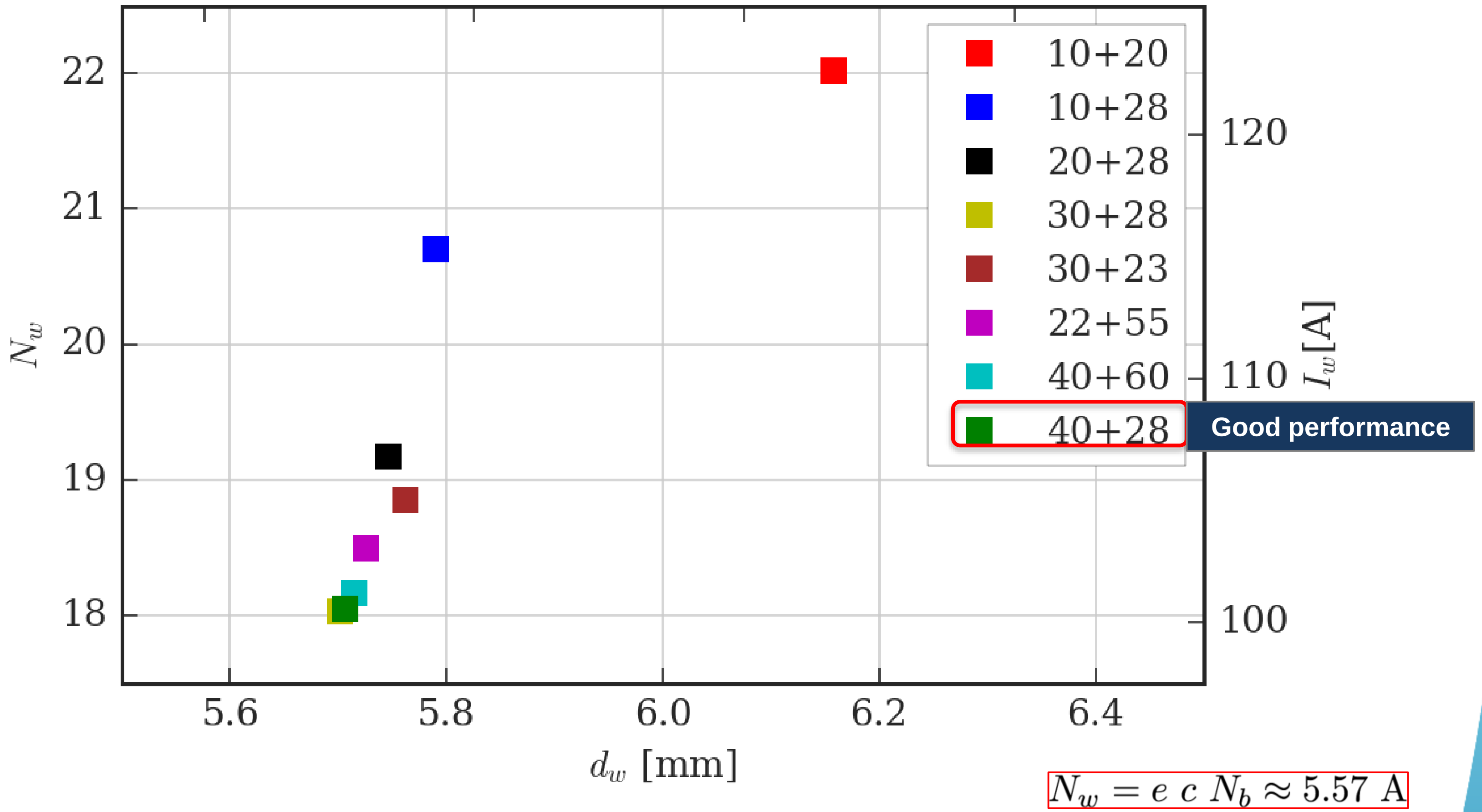
As expected (under the mentioned assumptions) the compensation is covering many more RDTs than the 4 used to set the BBCWs (green boxes). The p+q=1 and p+q=2 could be addressed by using “local” linear magnets (Q4s and the Q4 correctors).

IDEAL CASE: 2 BBCW for IP at s_{opt}=+-159 m



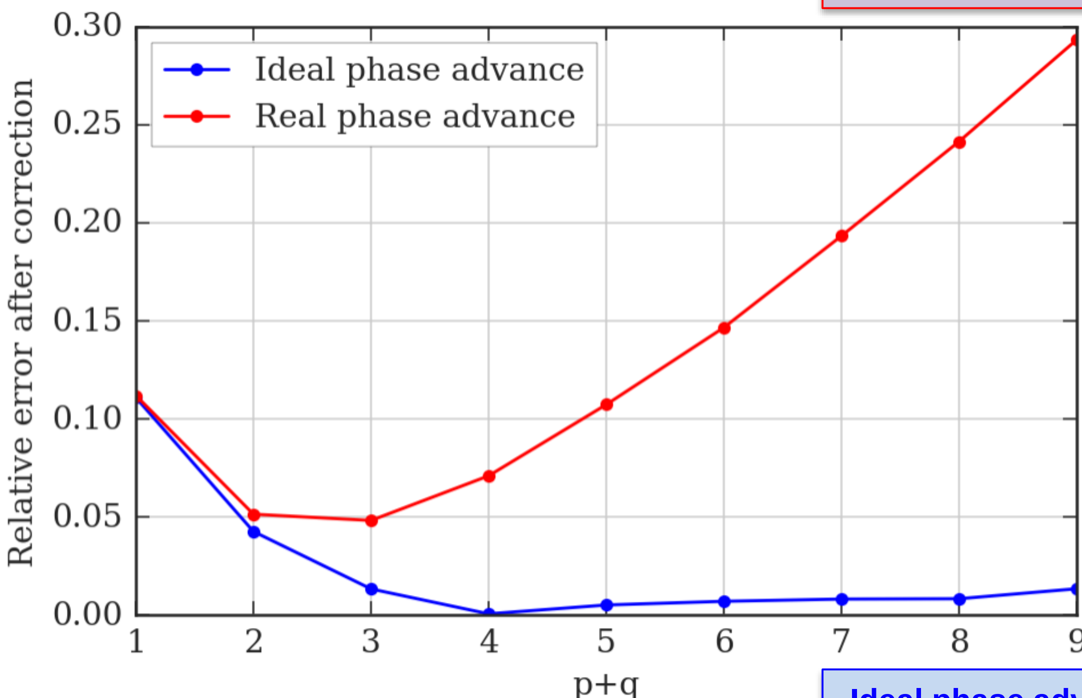
Averaging the anti-diagonal of the RDT map one can chose a convenient RDT minimization strategy. The minimization of 40+28+04+82 is the best among the considered cases.

IDEAL CASE: from RDT to I_w and d_w.

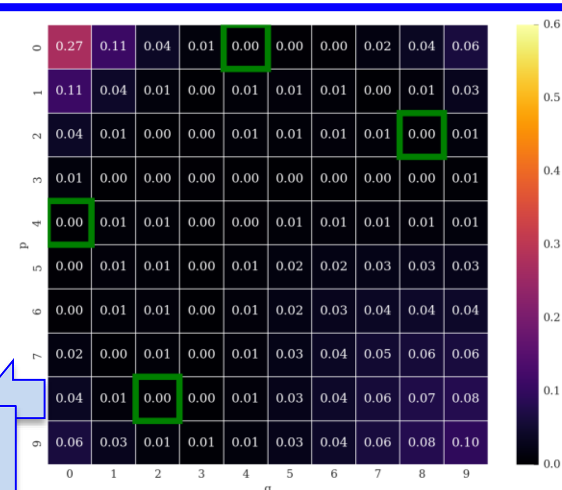


The d_w will depend on the crossing angle [back-up slides].
In the plot we assume a half-crossing of 150 urad.
This ideal case cannot be reached in MD (*s* and *x*-position limits).

IDEAL CASE: considering the phase advance.



Real phase advance considered



Ideal phase advance considered (β*→0)

One can quantify a posteriori the effect of the phase advance.

The compensation of the RDT does degrade. The compensation of detuning terms (Q-footprint compression) is not affected.

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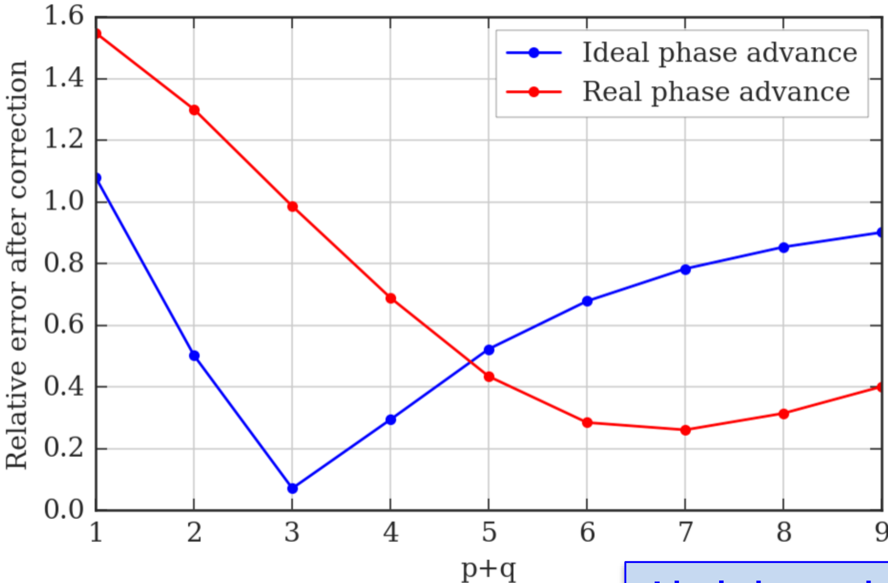
The MD results and the RDT

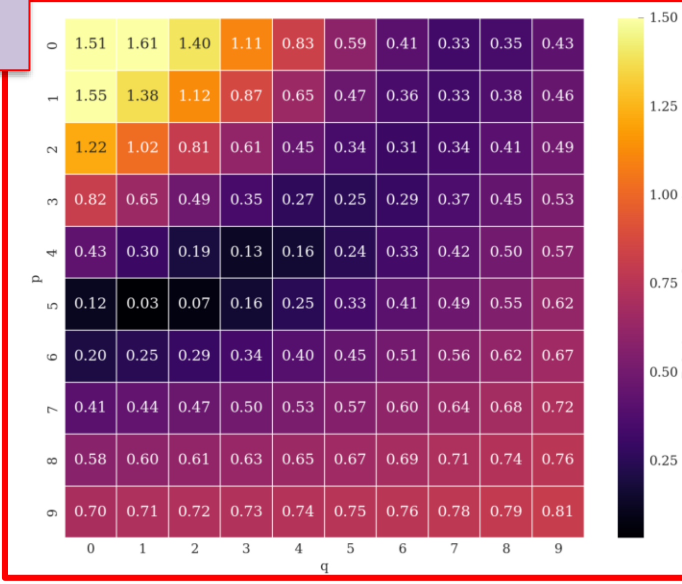
Very different from the ideal case:

- The BBCWs are not in the optimal s-position.
- The BBCWs are only in IP5.
- The BBCWs are not positioned symmetrically with the IP5 (~2 m asymmetry).
- The parameters adopted for the correction were $I_w^R = I_w^L = 350$ A , $d_w^R = 7.95$ mm, $d_w^L = 6.92$ mm and $\theta_c = 120$ μrad).

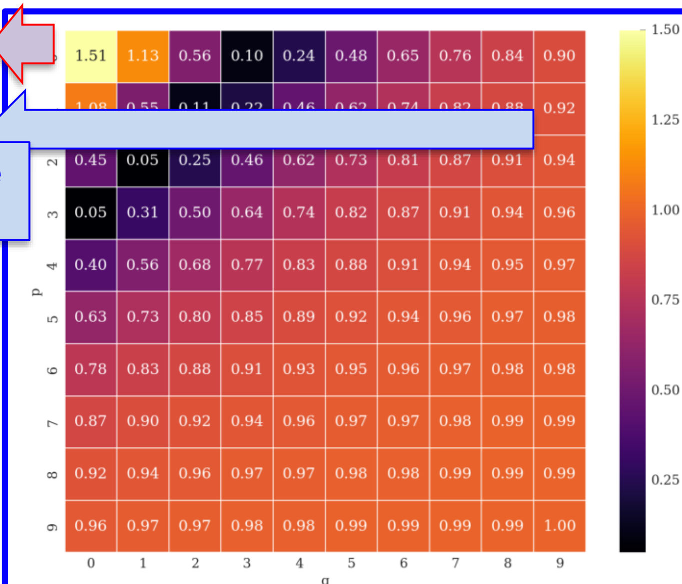
The MD results and the RDT



Real phase advance considered



Ideal phase advance considered (β*→0)



PRELIMINARY: the observed effect of the BBCW could be related to a partial compensation of the detuning terms.

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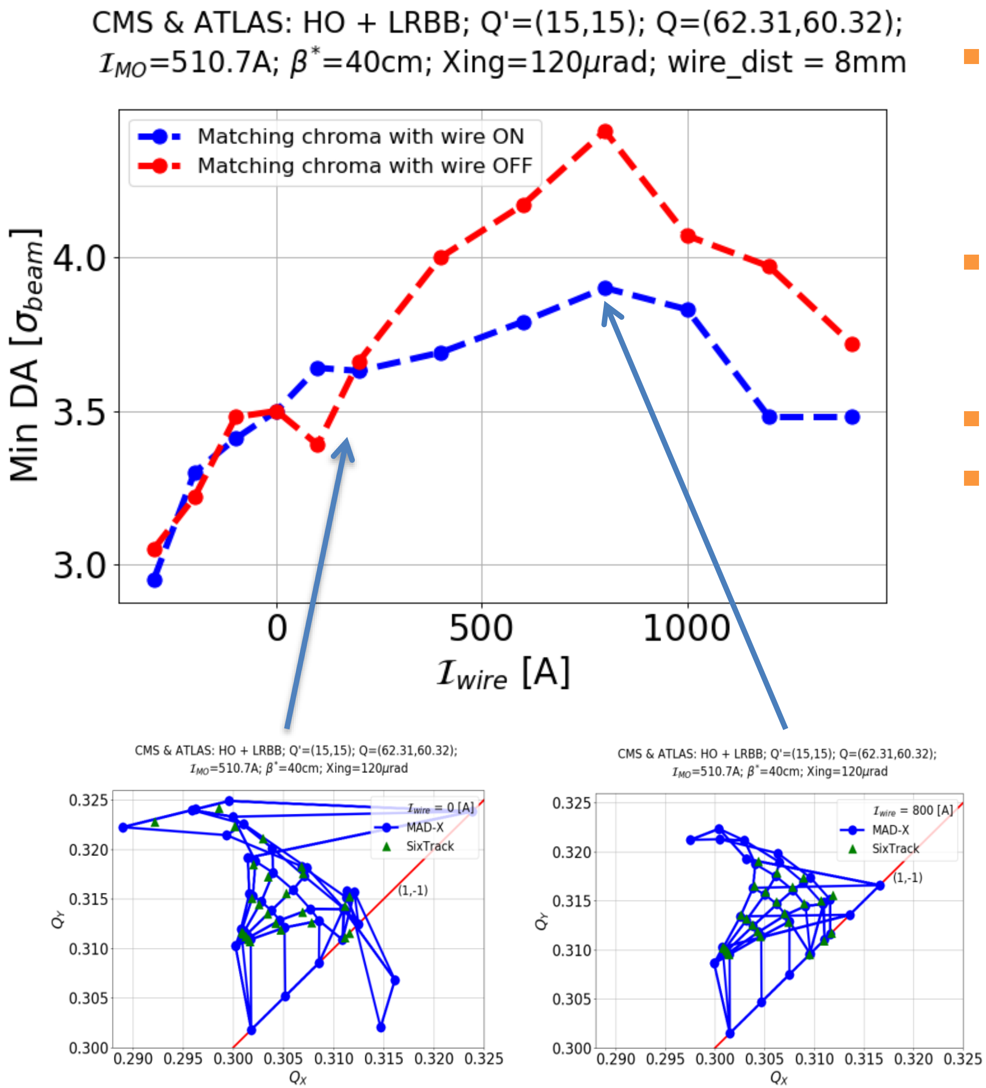
DA simulations with Wire in MD-like conditions I



- MD-like conditions: d_w=8 mm. LR in IR1/5 but wire only in IR1, real aspect ratio at wire position, phase advances.
- A modest gain of DA is observed for 8 mm wire-beam distance.
- Optimal DA for 800 A.
- With no rematch of the chromaticity (as in the MD), the gain of DA is improved.

- Good agreement between footprints from MADX and Sixtrack.
- Improvement observed but no clear identification of the optimum.

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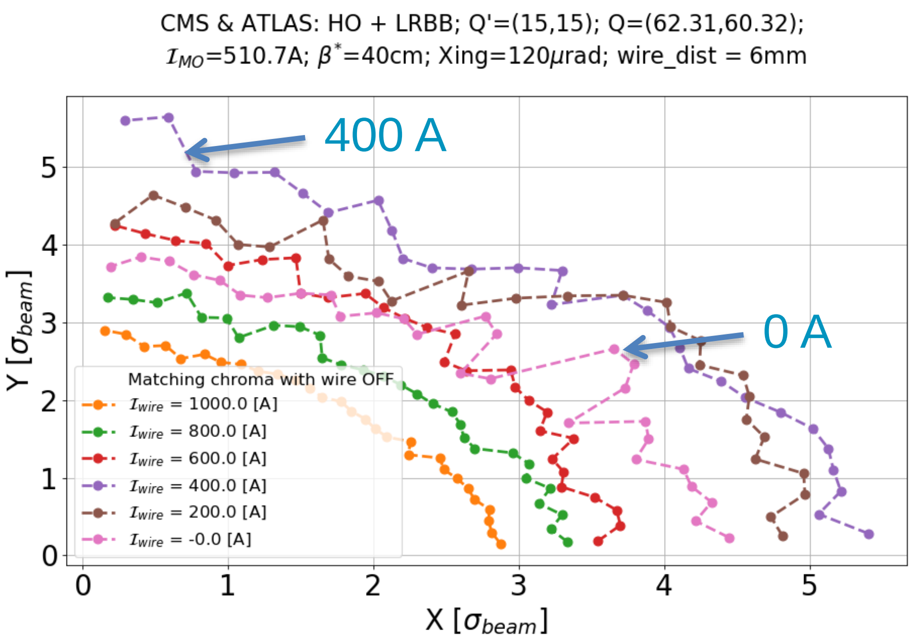
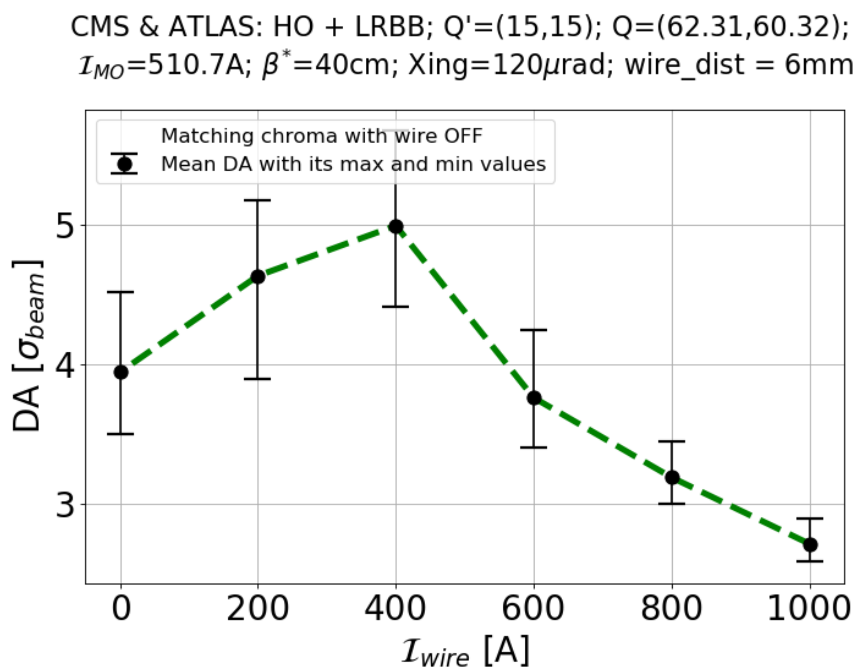
DA simulations with Wire in MD-like conditions II

- Push d_w to 6 mm
- Still not ideal conditions: LR in IR1/5 but wire only in IR1, aspect ratio at wire position, phase advances.
- **1σ** (@2.5 μm) DA gained for an optimal wire current of ~400 A.
- Clear improvement over all the angles.





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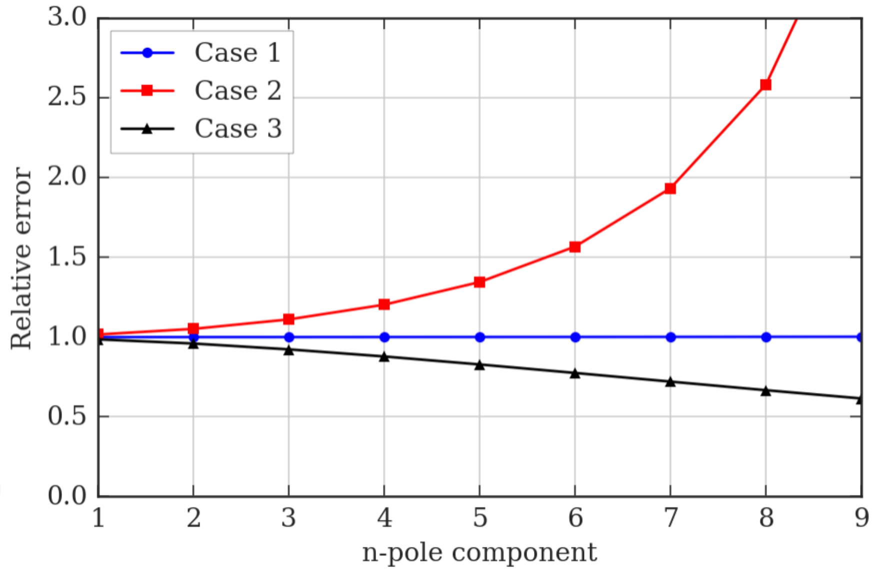
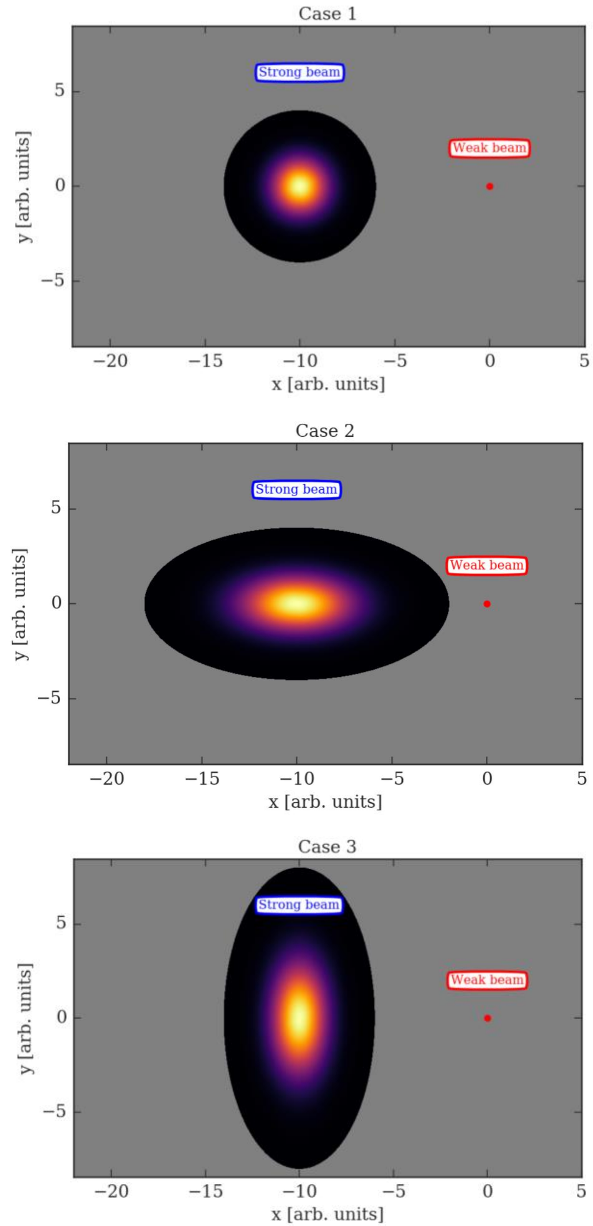
“Strong beam”-wire equivalence

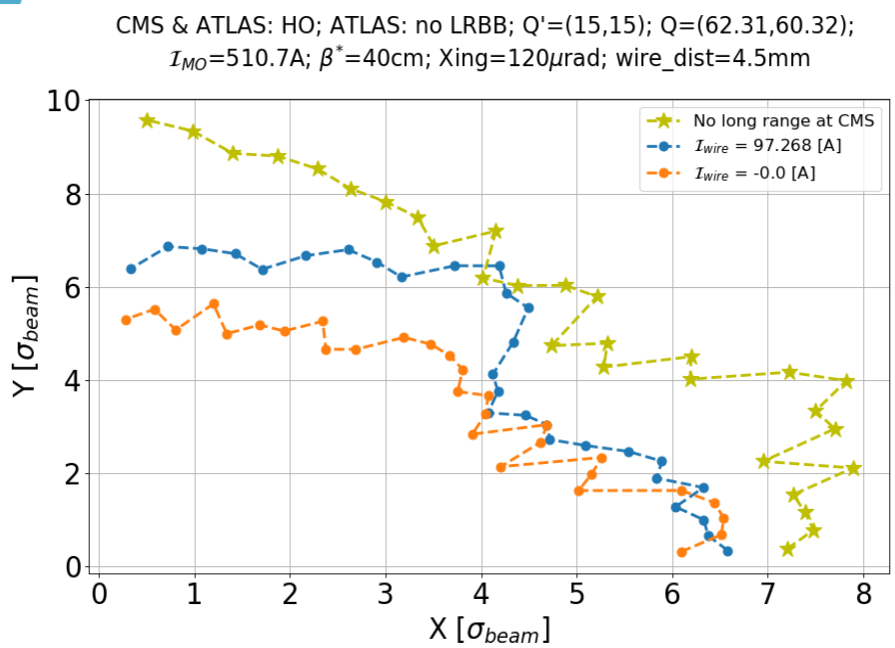
- For $\beta_x \neq \beta_y$ the “strong beam”-wire equivalence is not valid anymore
- We compare the strong beam field and the wire field in terms of multipoles
- Case 1: $\beta_x = \beta_y$, perfect equivalence
- Case 2: $\beta_x = 4^*\beta_y$, see plot below
- Case 2: $\beta_y = 4^*\beta_x$, plot below
- We assume bi-Gaussian density (4 σ cut)



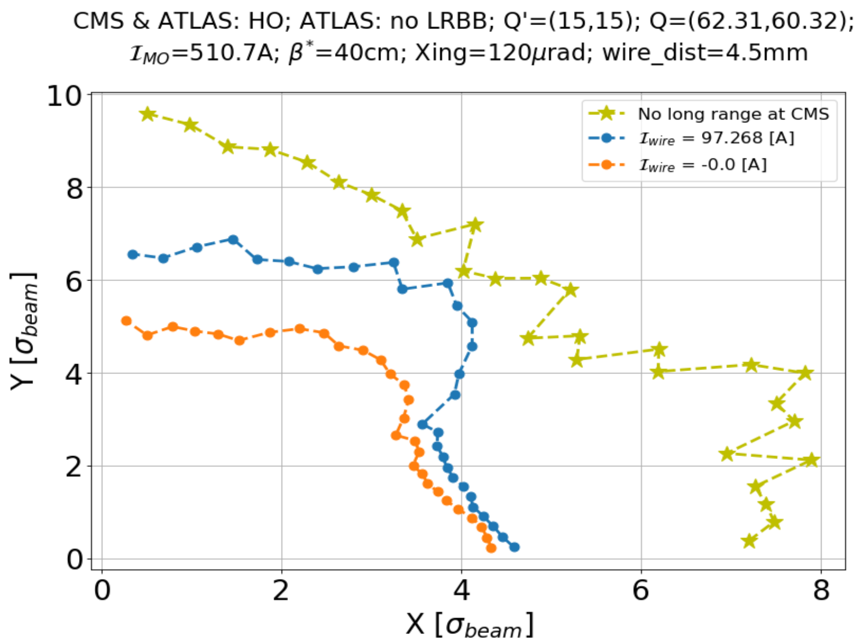


"Strong beam"-wire equivalence: tracking

Standard Strong Beam



Zero-emittance-long-range Strong Beam



K. Skoufaris

- The zero-emittance-LR strong beam does not show a better DA.
- Effect of phase advance? Plans to test with the wire at ~70 m for better phases.

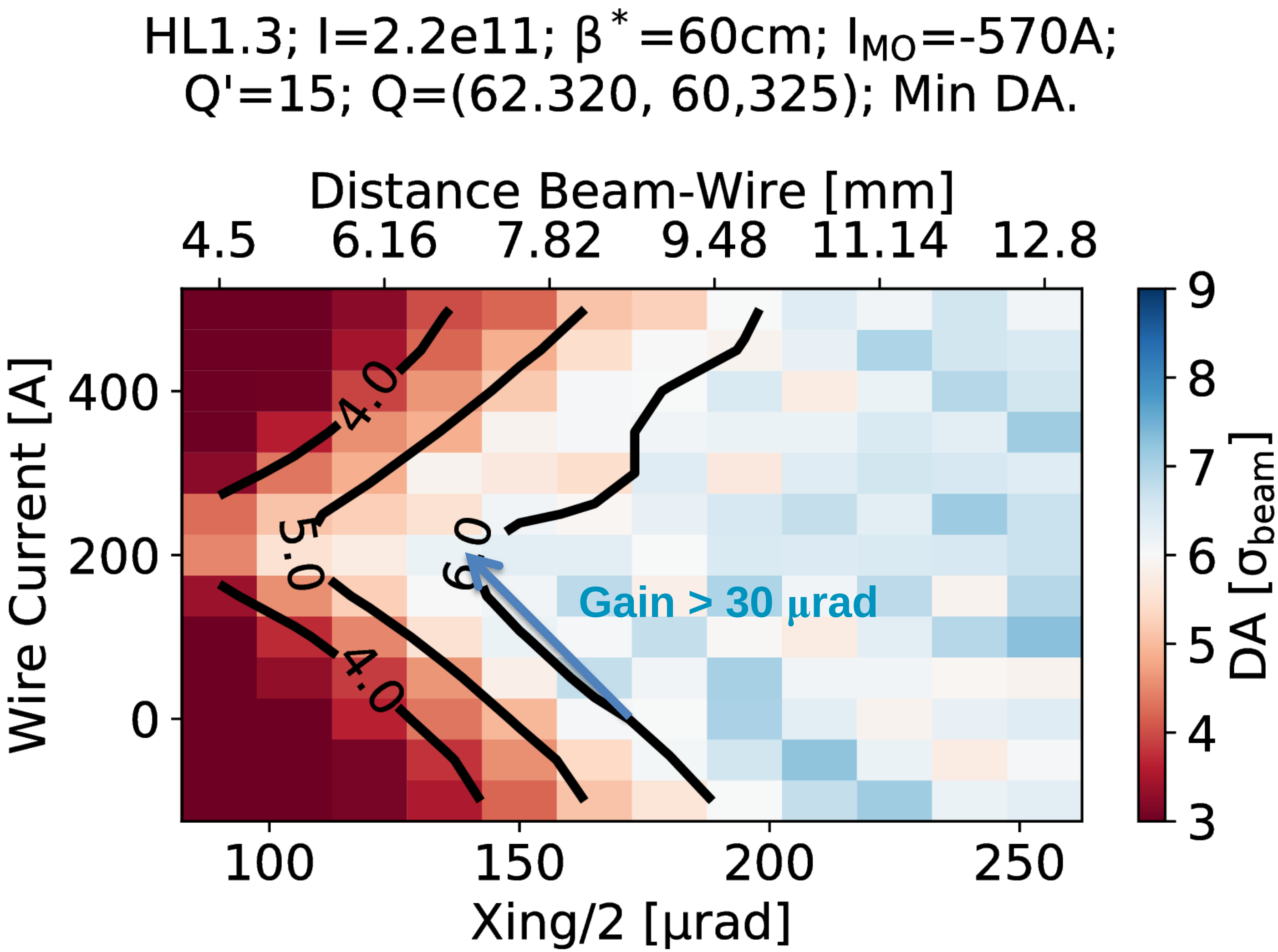
First attempts of BBCW in HLLHC1.3

- B1 tracking with **operational settings** for emittance, tunes, chroma, octupoles.
- **4 wires** (L/R IP1/5) installed in the crossing plane.
- The wires are arbitrarily placed at **+/-150m** from the IPs.
- The **distance** is tuned so that the beam-wire normalised separation is the same as the normalised crossing.
- Likely a **suboptimal** configuration to be further refined.

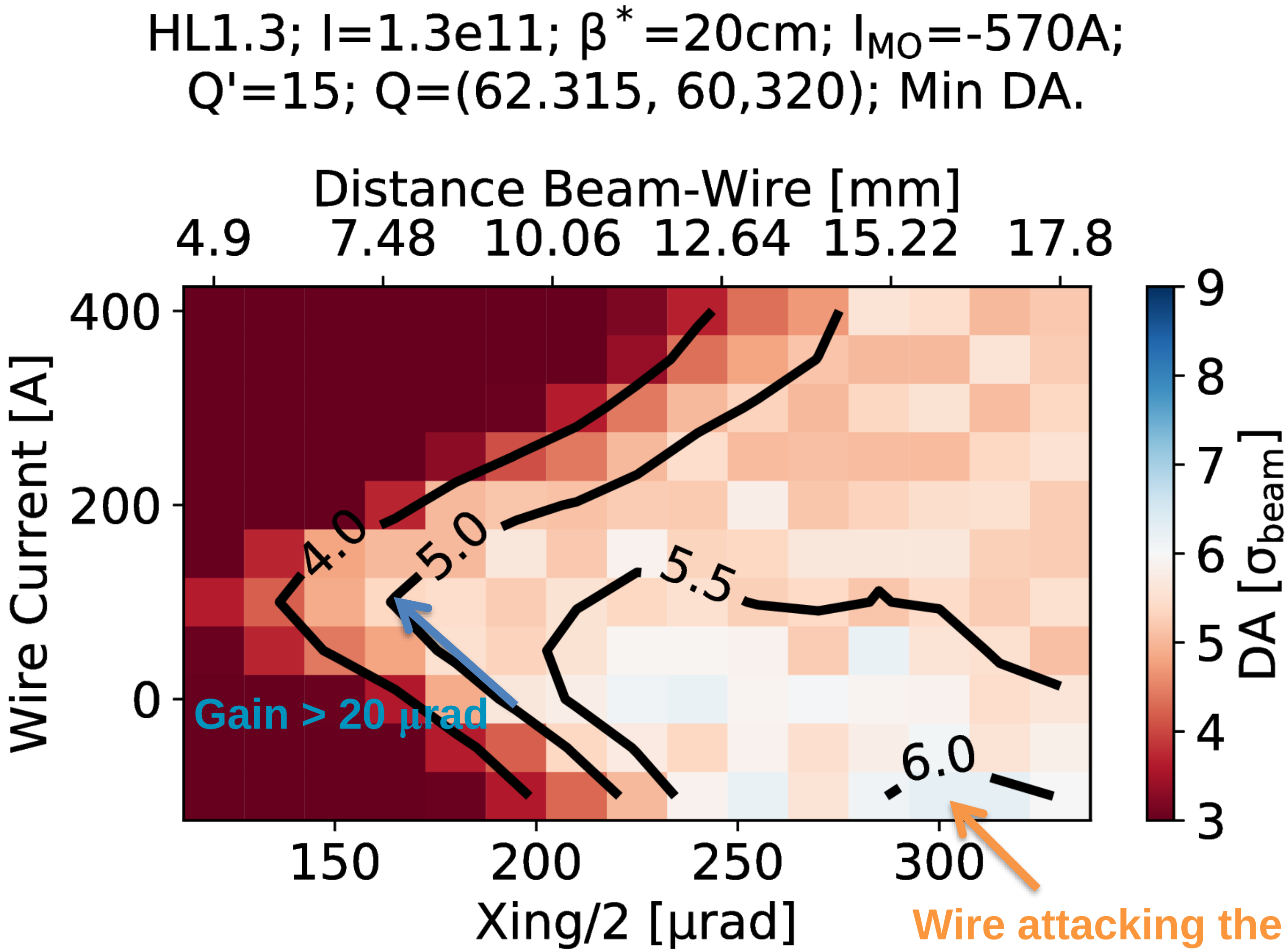
β* = 60 cm	H Beta [m]	V Beta [m]
wire_l1.b1	1052	1181
wire_r1.b1	1178	1054
wire_l5.b1	1054	1182
wire_r5.b1	1181	1055

β* = 20 cm	H Beta [m]	V Beta [m]
wire_l1.b1	3006	3641
wire_r1.b1	3649	2999
wire_l5.b1	2995	3645
wire_r5.b1	3636	3003

Wire Compensation at the beginning of the fill



Wire Compensation at the end of levelling



Wire attacking the extra octupole strength?

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Conclusions and plans

- During the MD2202 it was observed for the first time in LHC the effect of a direct compensation of the BBCW.
- Given the constraint on the minimal d_w we used the maximum current. The analytical approach showed that the MD settings reduce by 75% the linear detuning due to the BBLR in IR5.The tracking studies showed the improvement of DA (with 400-800 A current with similar d_w).
- The tracking for the HL-LHC shows a beneficial effect of the BBC also with sub-optimal positioning: iteration with the analytical model and the tracking will be the next step.
- Presently working in the benchmarking of DA studies and analytical model with respects the phase and strong-beam assumptions.
- In MD3 we plan to perform a systematic I_w scan with <=5.5 σ_{coll} and θ_c=120 μrad.
- For HL-LHC, need to find a common strategy between BBLR octupoles/wires compensation and coherent effects.

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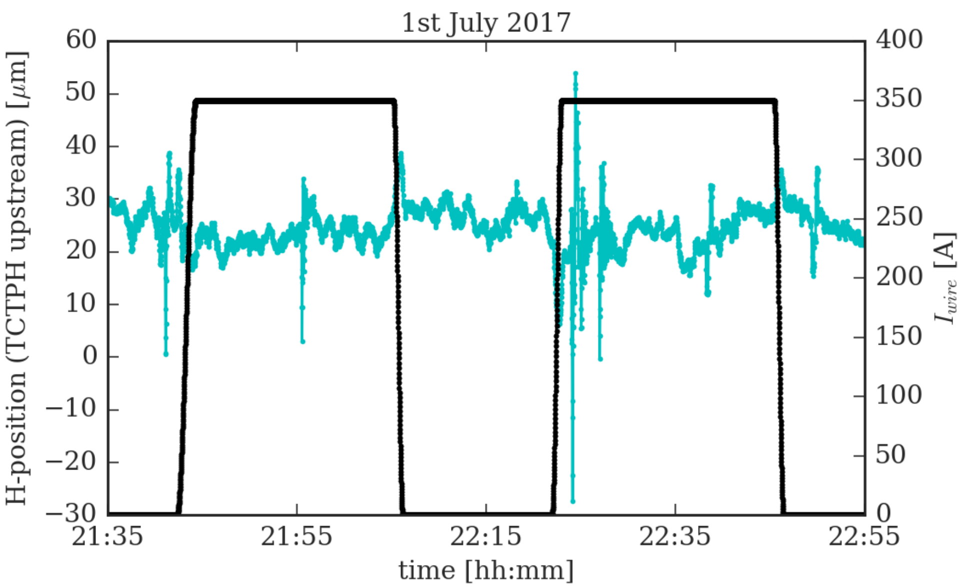
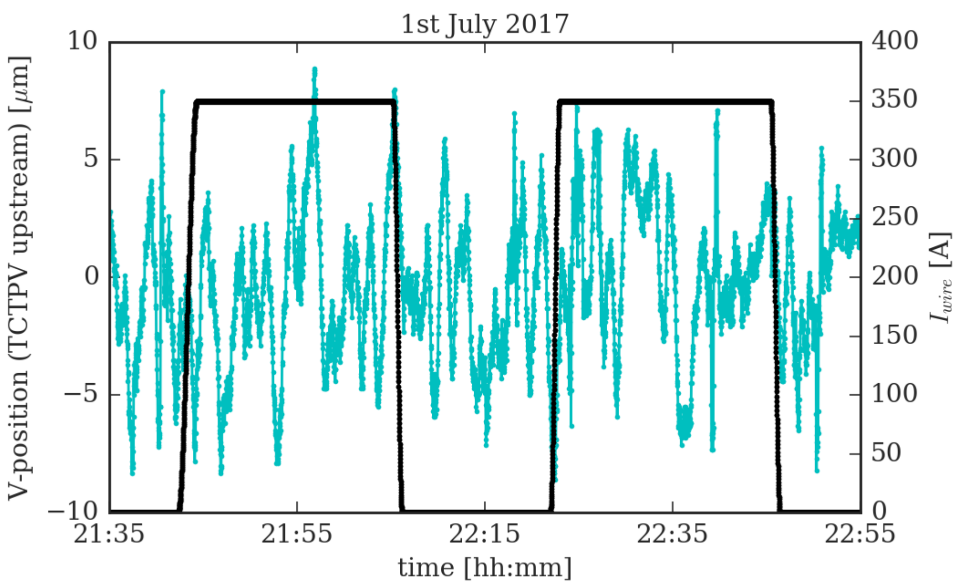
BACK-UP SLIDES

BBCW MD: sanity checks on H/V-position

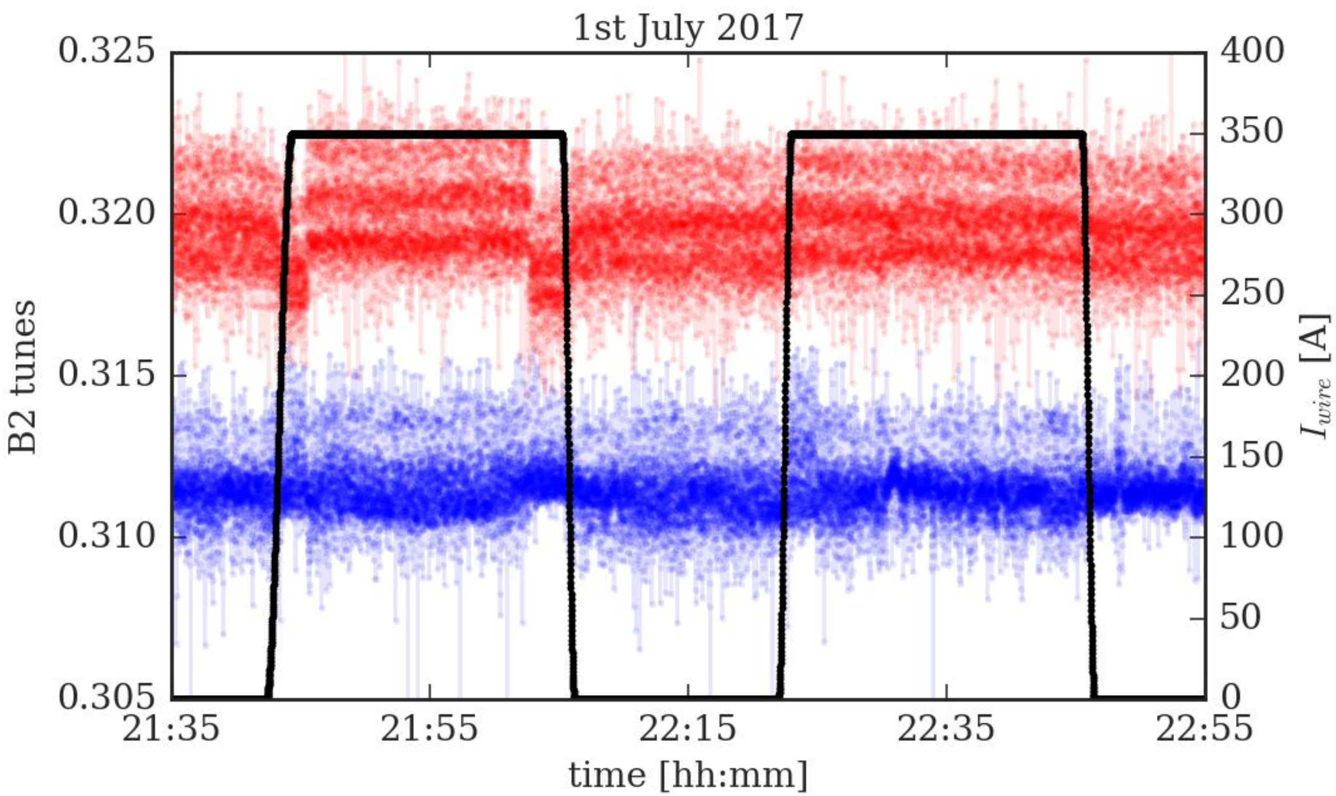
- The H-position of the beam is well under control.



- The V-position and correctors behaviour confirm a very good V-alignment of the BBCW.

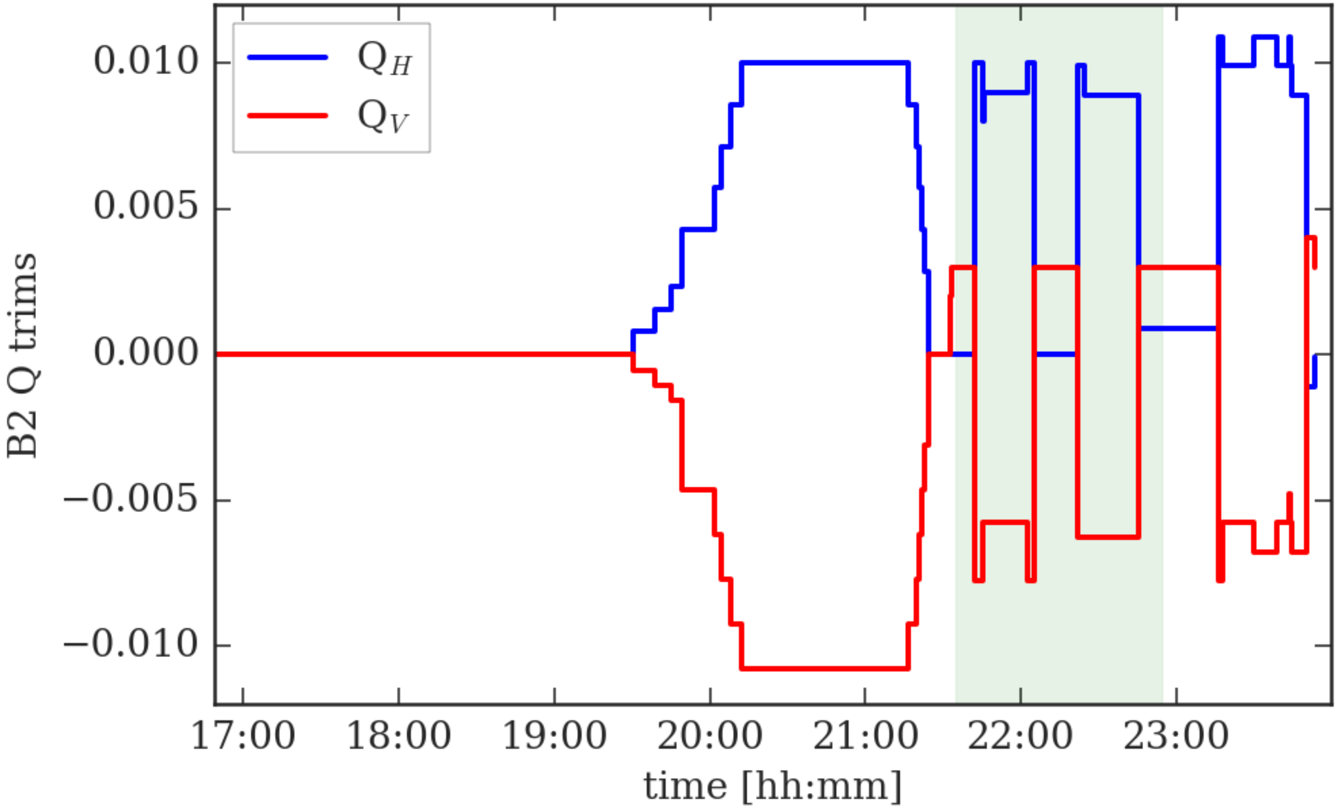


BBCW MD: sanity checks on tunes



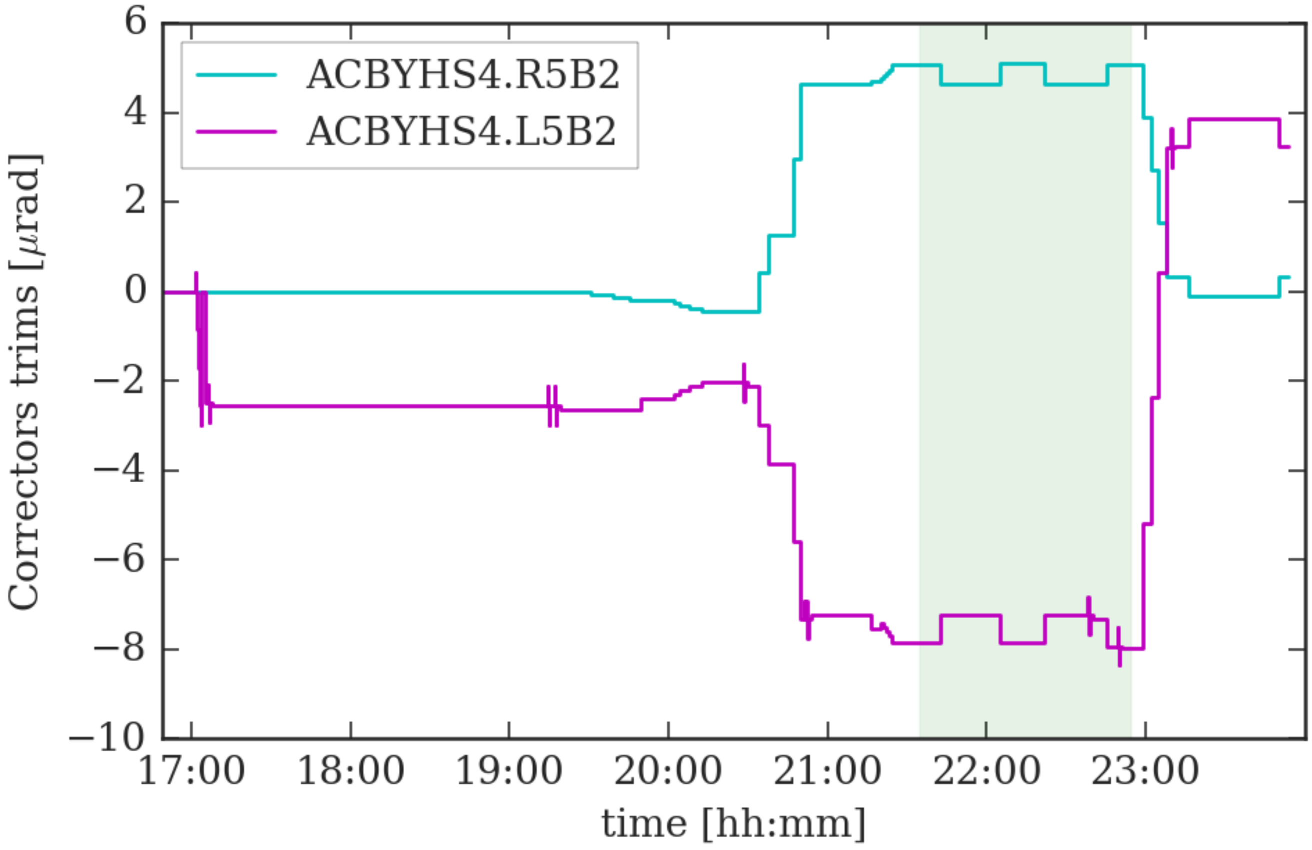
- The tunes feedback is off during collision. The Q-feedforward is working as expected allowing to keep constant the tune during the ON/OFF cycles of the BBCW.

BBCW MD: Q trims



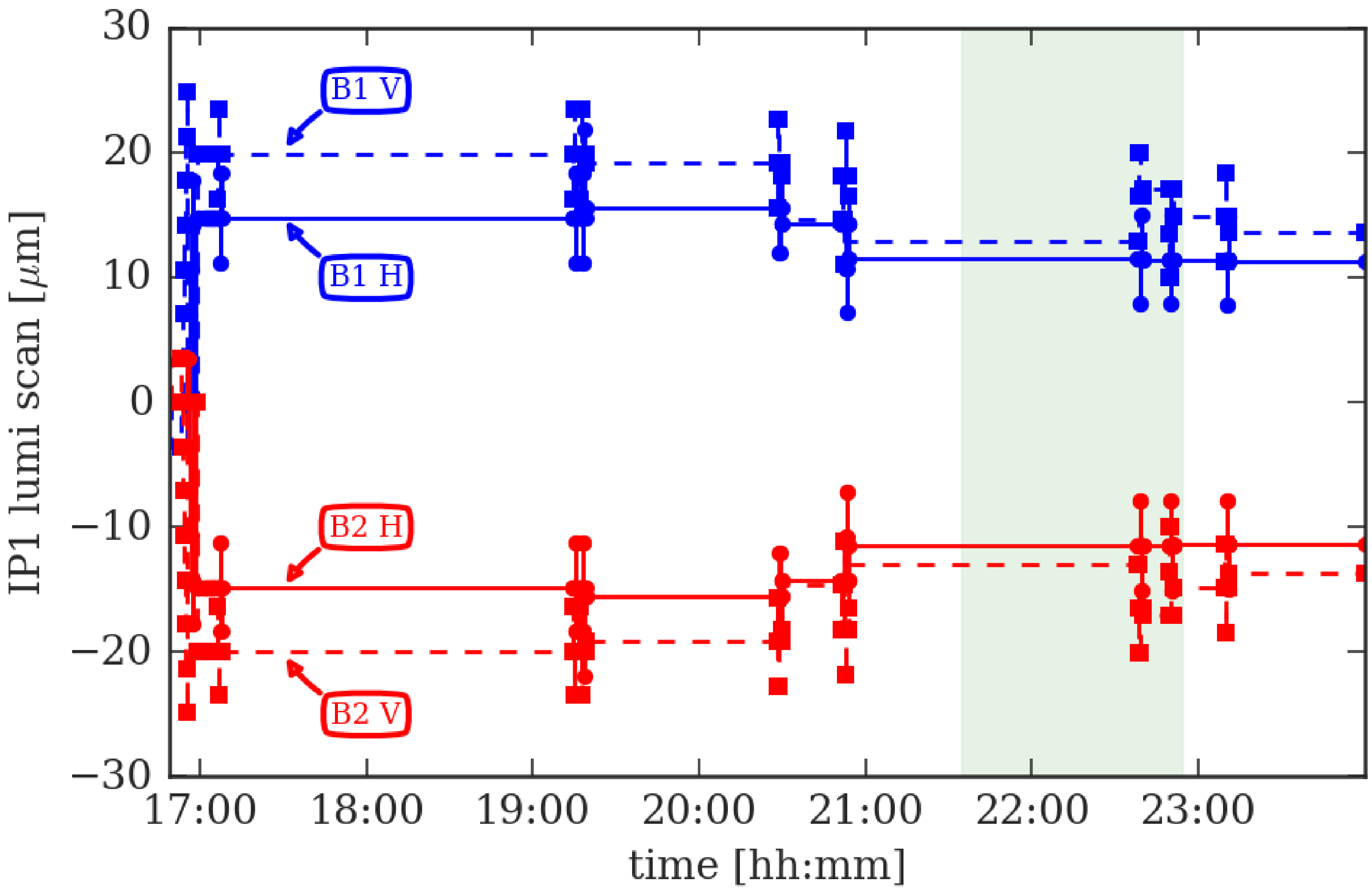
The Q-trims are mostly due to the feedforward.

BBCW MD: dipolar trims

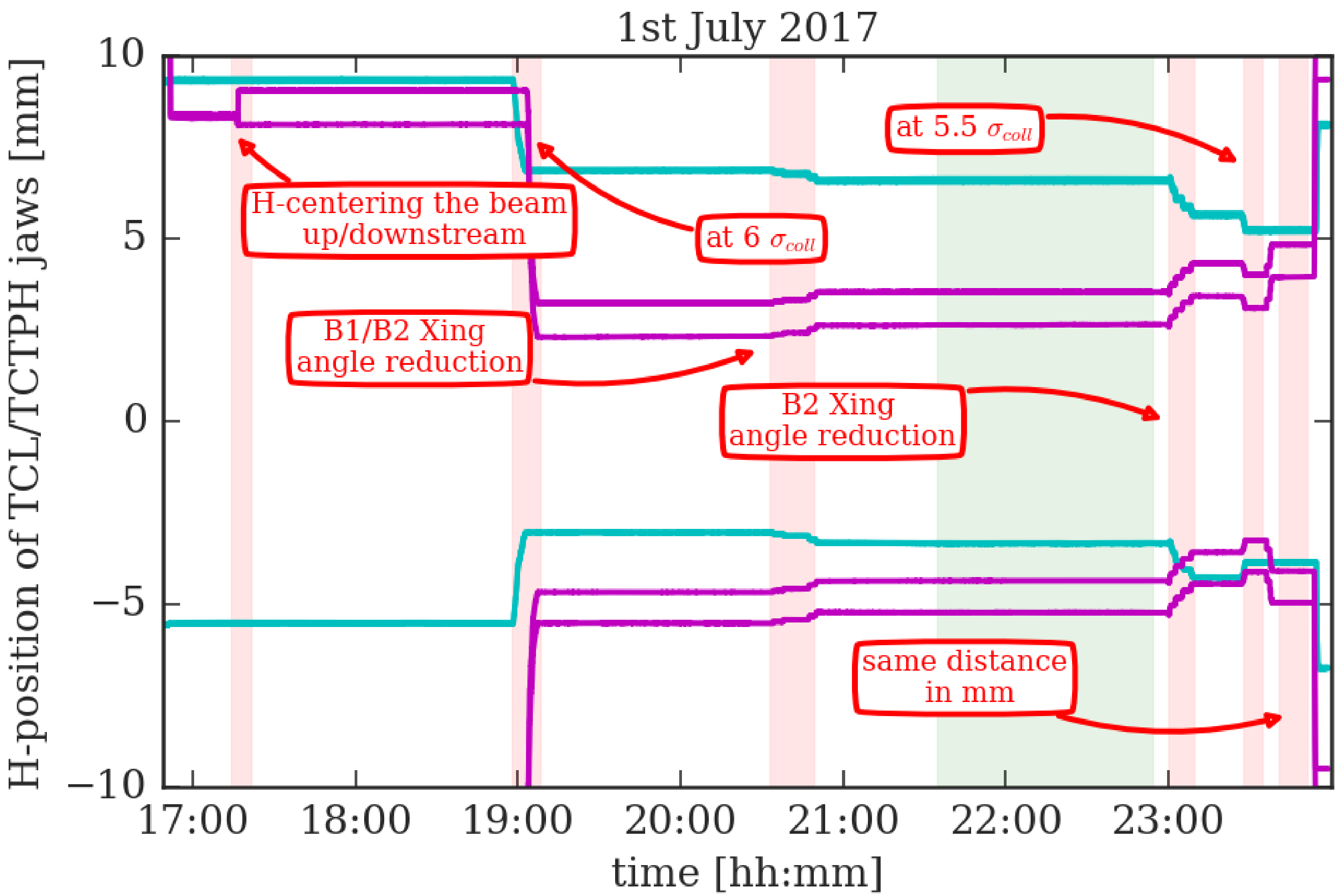


The correctors trims are mostly due to the crossing angle settings.

BBCW MD: optimizing HO collision

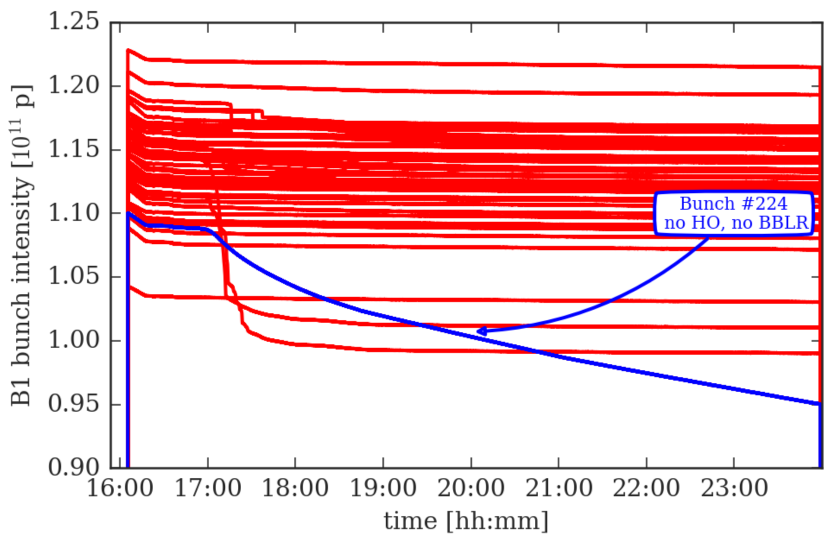


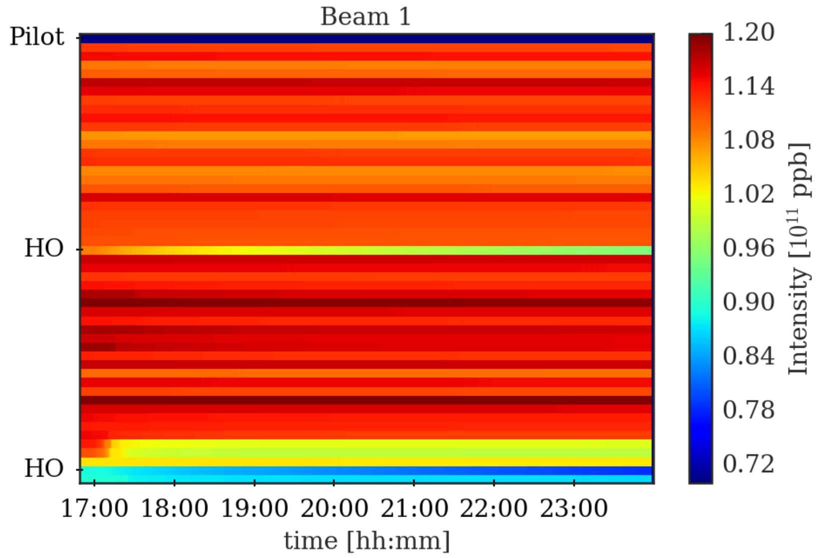
BBCW MD: wires H-positioning

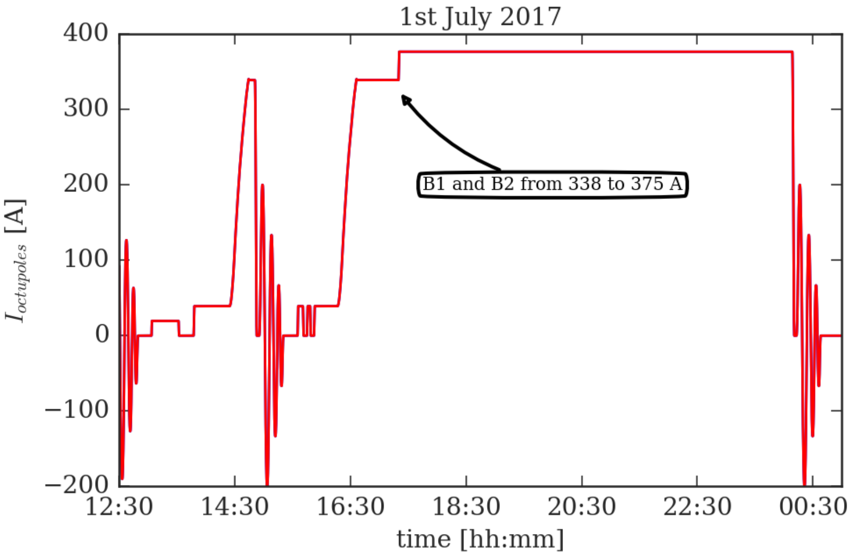


The hectic activity on the BBCW positioning.

BBCW MD: instability of B1



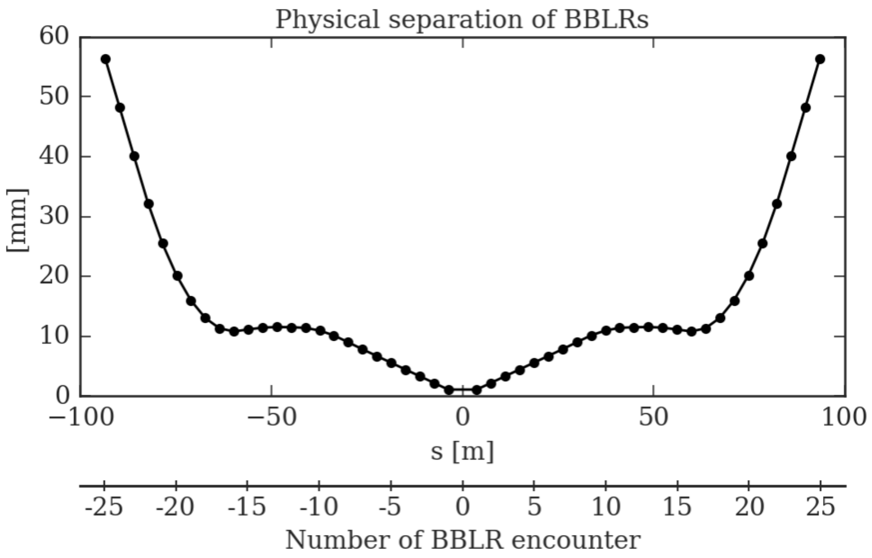


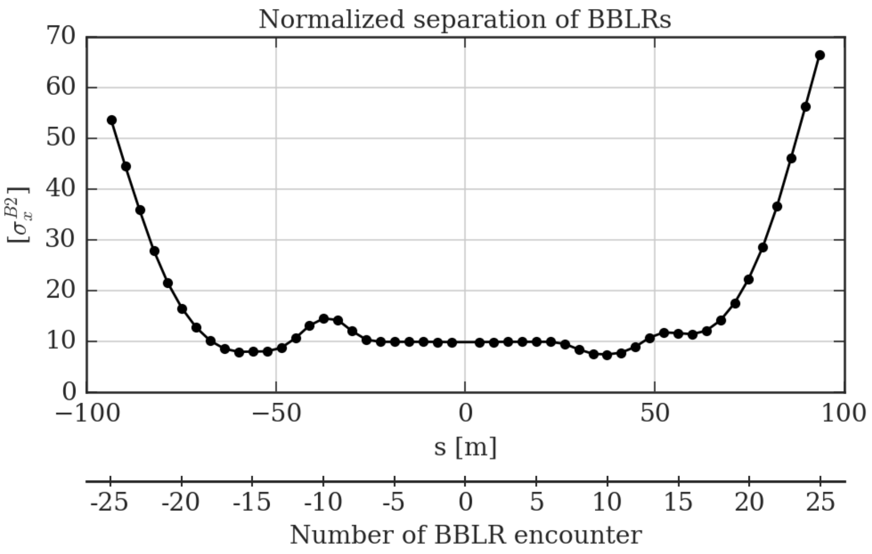


- During next MD we will use stronger octupole settings to avoid the instability of the non-colliding bunches in B1.

ATS 2017 optics

	NAME	X	PX	Y	PY	BETX	BETY	sigma_x at 3.5 um at 6.5 TeV [mm]
7062.030793	TCL.4L5.B2	1.527841e-03	0.000054	0.003836	-4.970527e-05	845.954861	1327.127536	0.653755
7212.060793	IP5	1.936385e-15	-0.000150	-0.001500	-9.267840e-15	0.400000	0.400000	0.014216
7360.005793	TCTPH.4R5.B2	-1.422381e-03	0.000034	0.002863	3.456410e-05	1349.329513	903.299673	0.825659

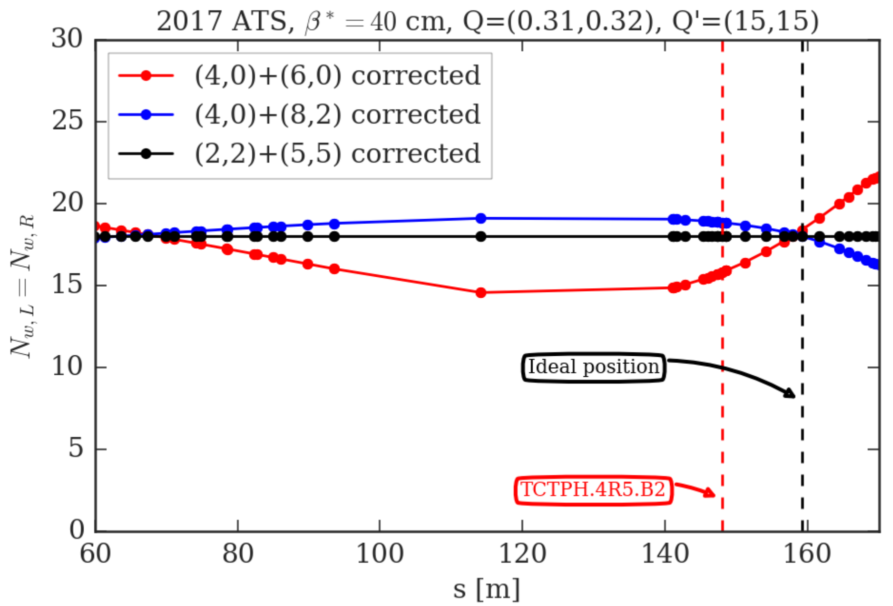


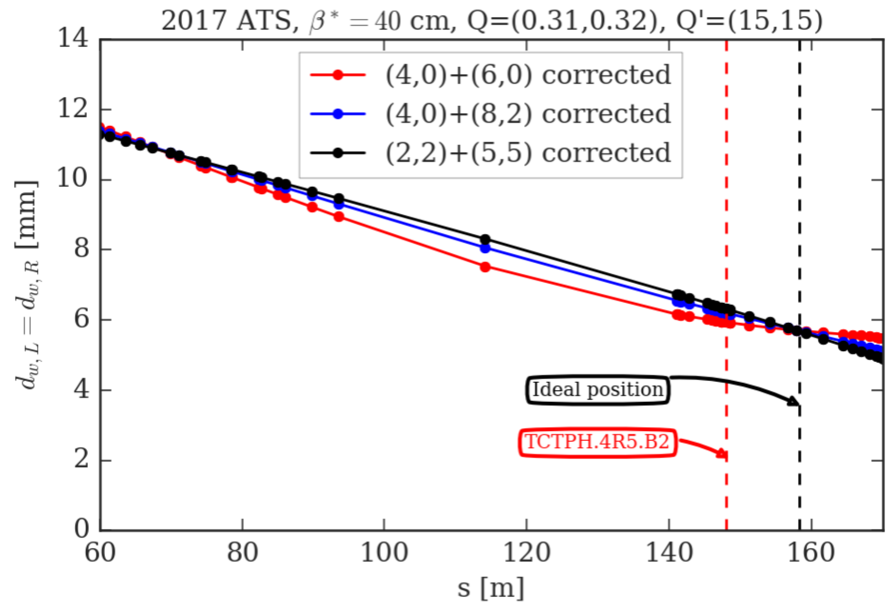


RDT criterion for ATS 2017 and θ_c=150 μm

By plotting the $N_w(s)$ and $d_w(s)$ for different RDT minimization strategy, one sees there are specific s-positions, s_{opt}, that minimizes more than the usual 4 RDTs.

The BBCW is positioned ~10 m apart with respect to the optimal position.





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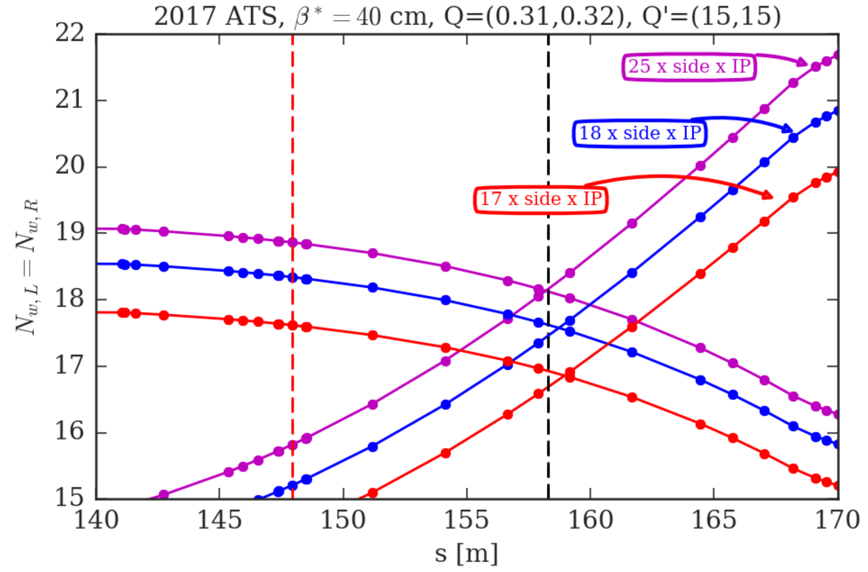
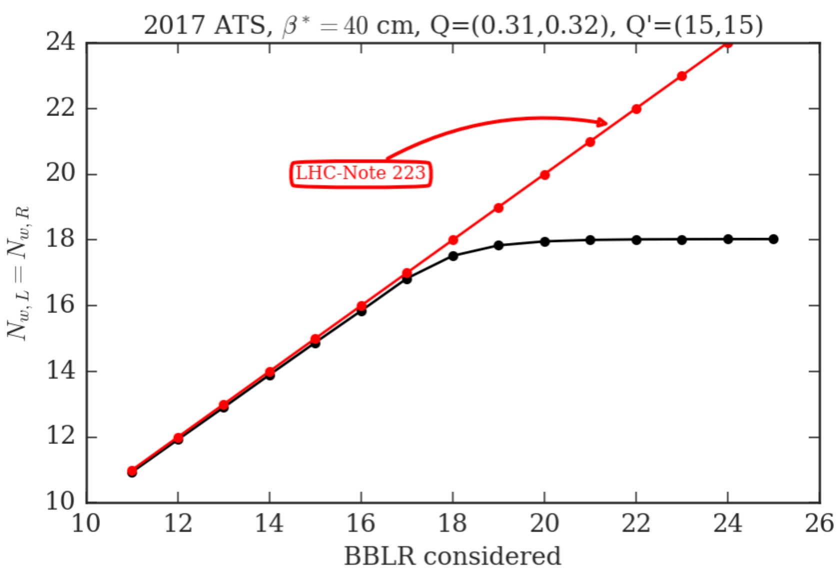
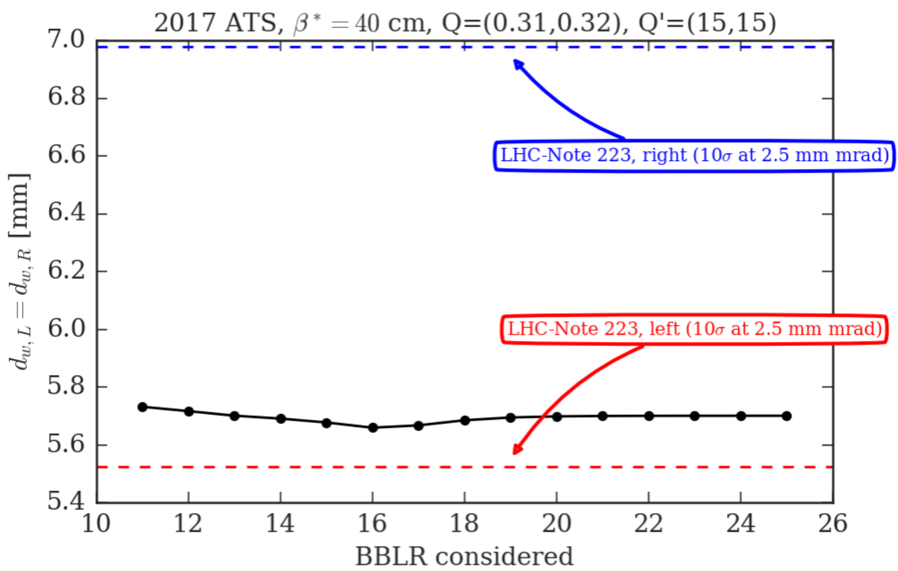
Convergence of BBLR with RDT criterion

- Does s_{opt} depend on the BBLR considered?
- How many BBLRs should be considered for its convergence?
- What about the convergence of N_w and d_w?

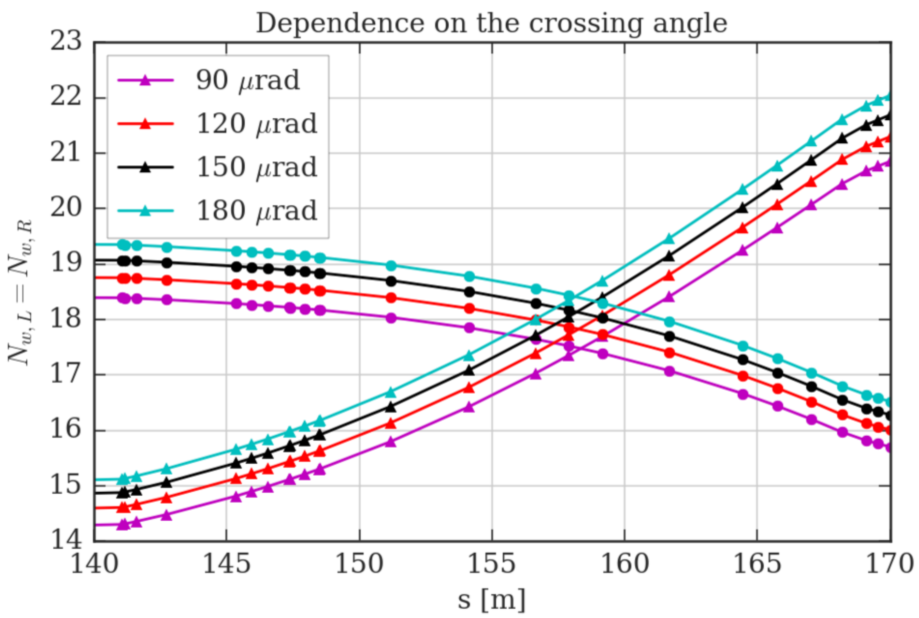


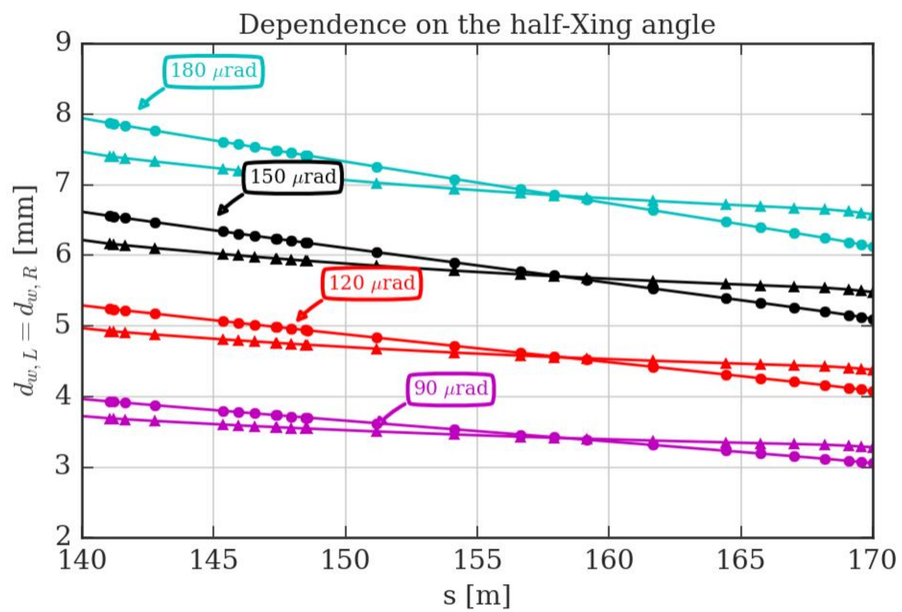




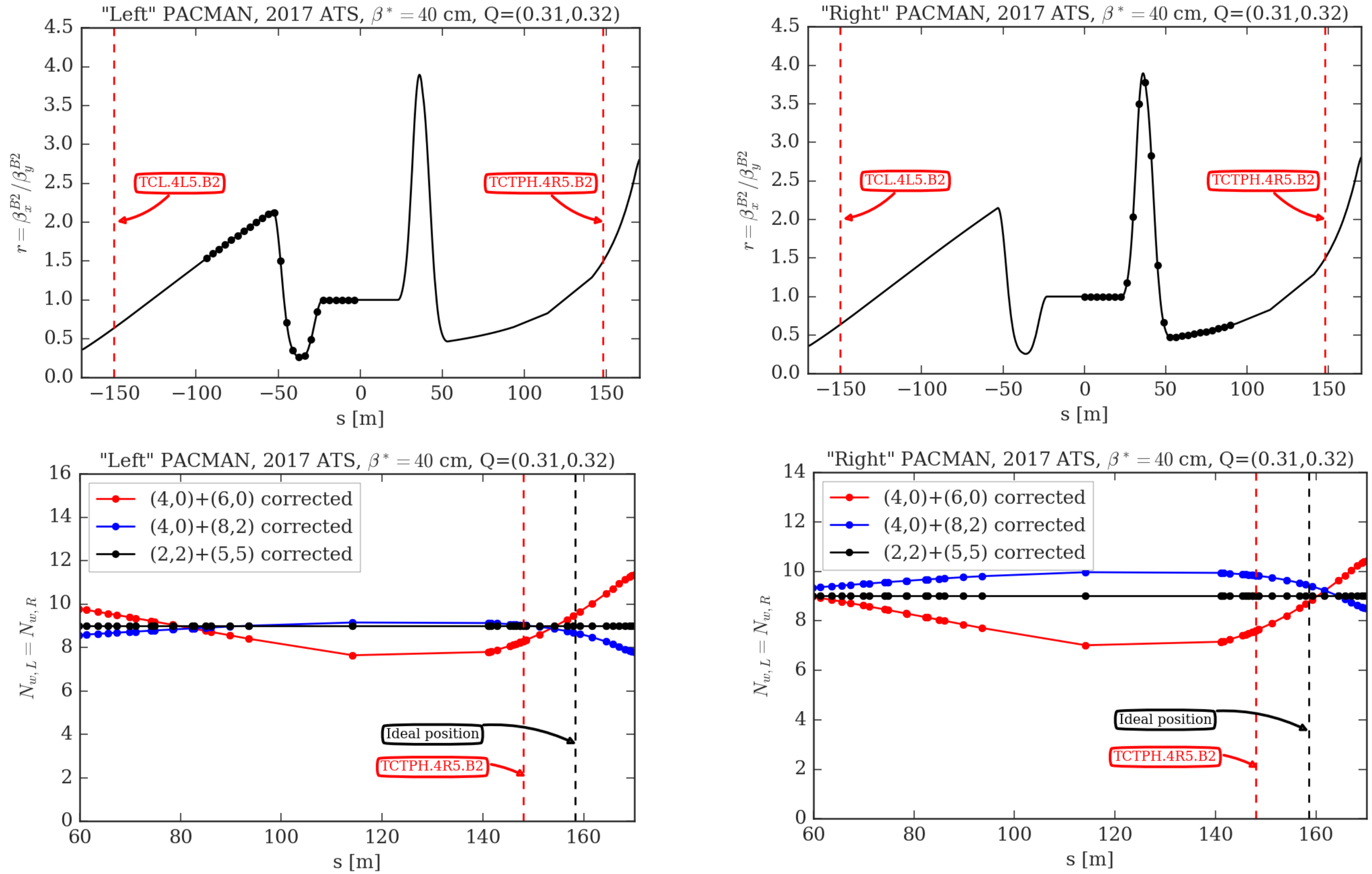
s_{opt}, N_w and d_w on crossing angle

- There is no dependence of s_{opt} on the crossing angle.
- N_w dependence on the crossing angle is marginal (smaller crossing angle, smaller N_w).
- d_w is linearly dependent on the crossing angle.





PACMAN bunches and s_{opt}

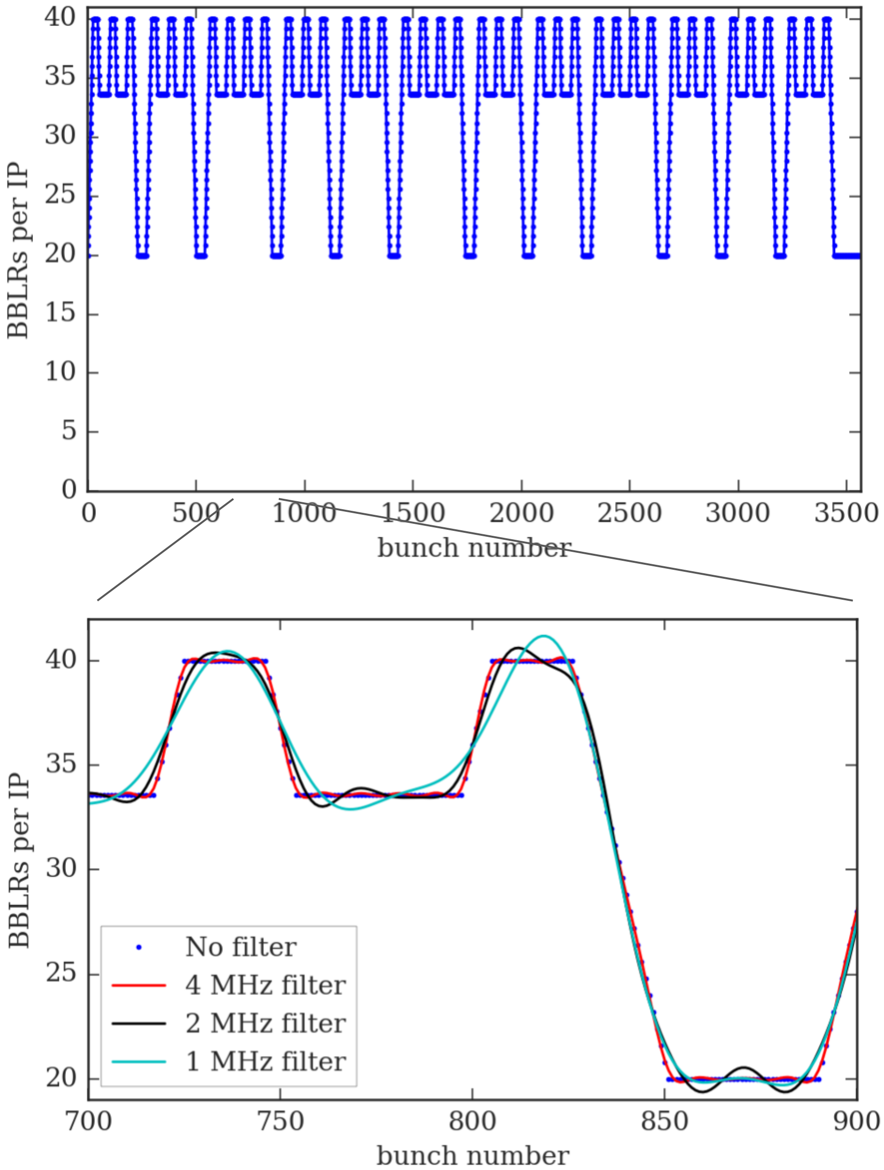


The s_{opt} depends on the PACMAN pattern.

PACMAN bunches and I_w modulation

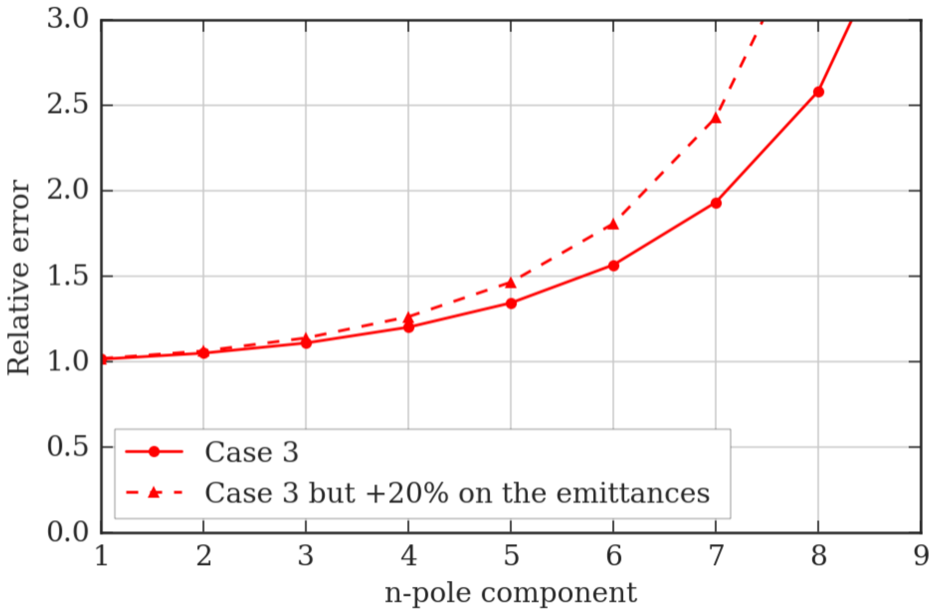
The needed I_w modulation BW is of the order of 4 MHz (x10 lower than the bunch frequency).

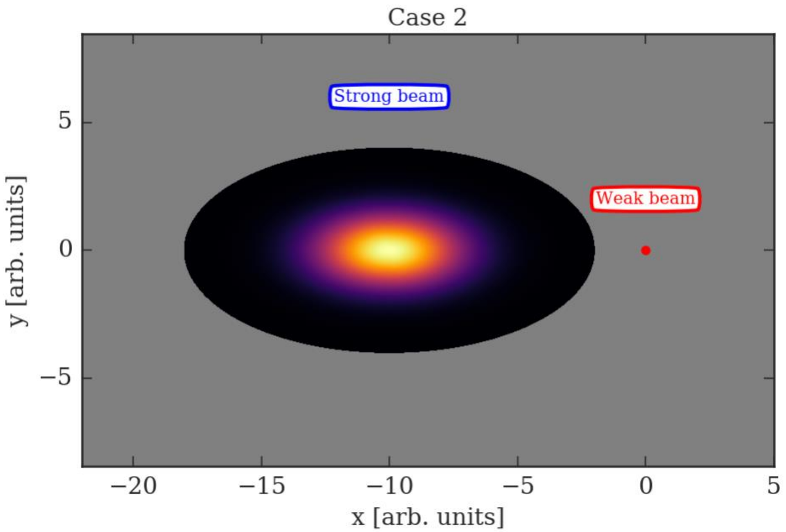
The wavelength in vacuum of a 4 MHz EM wave is ~75 m.

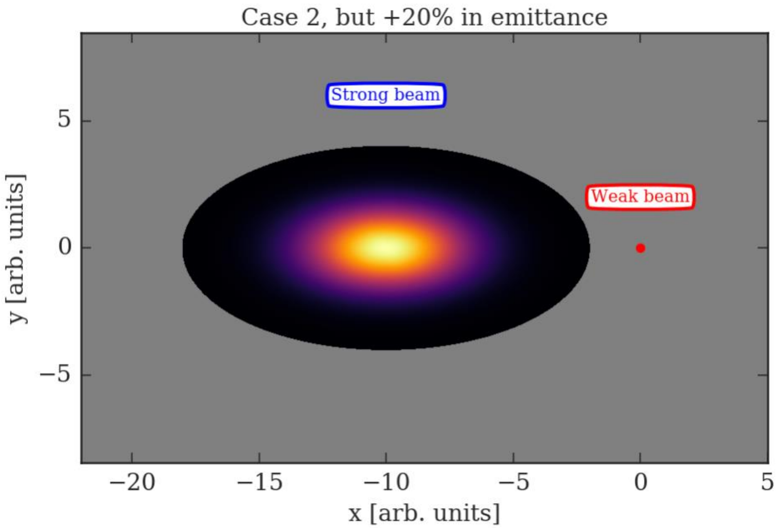


“Strong beam”-wire equivalence II

- Case 2: what if the emittances of the strong beam increases by 20%?

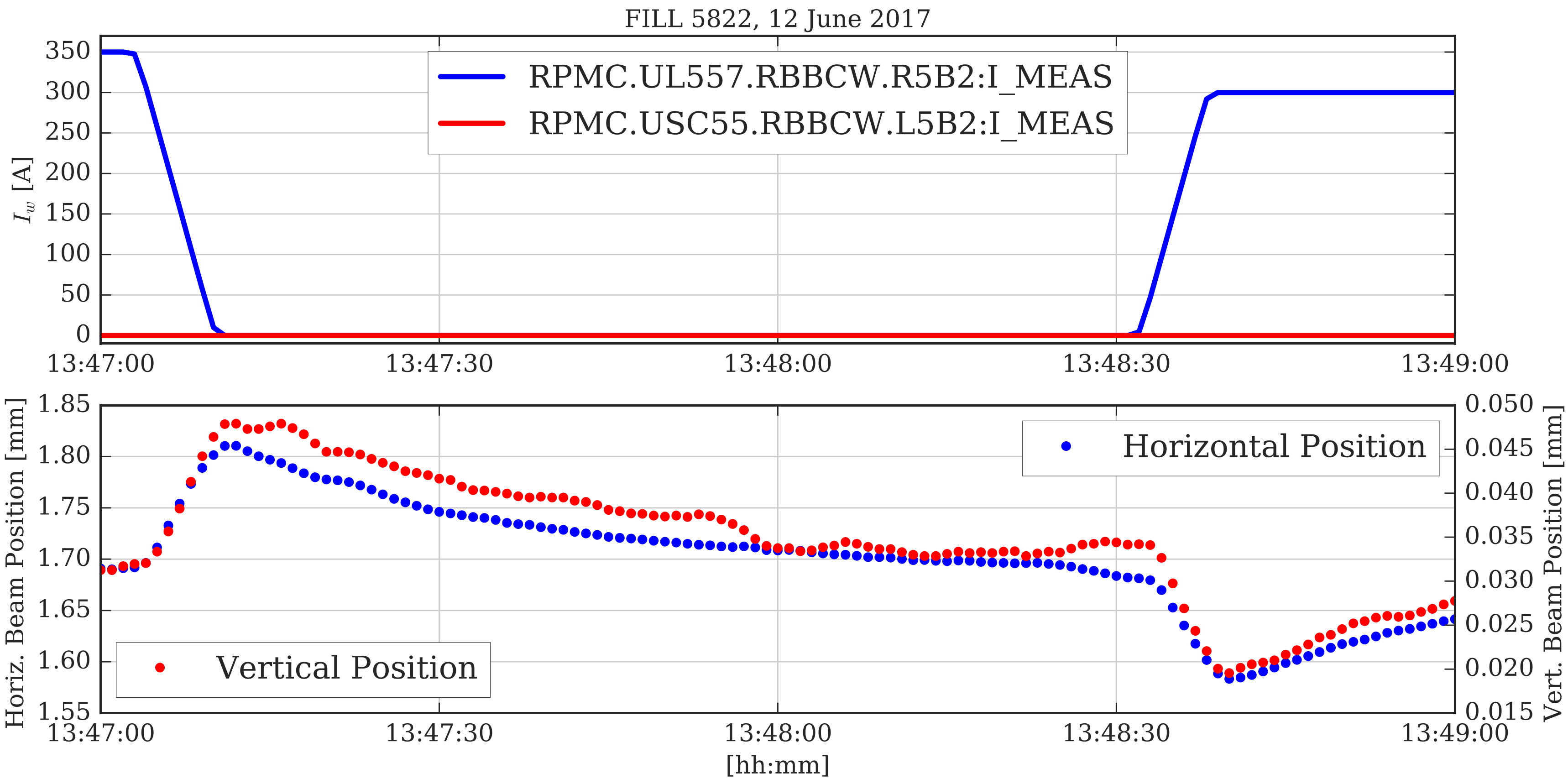






What is the time constant of the CO feedback?

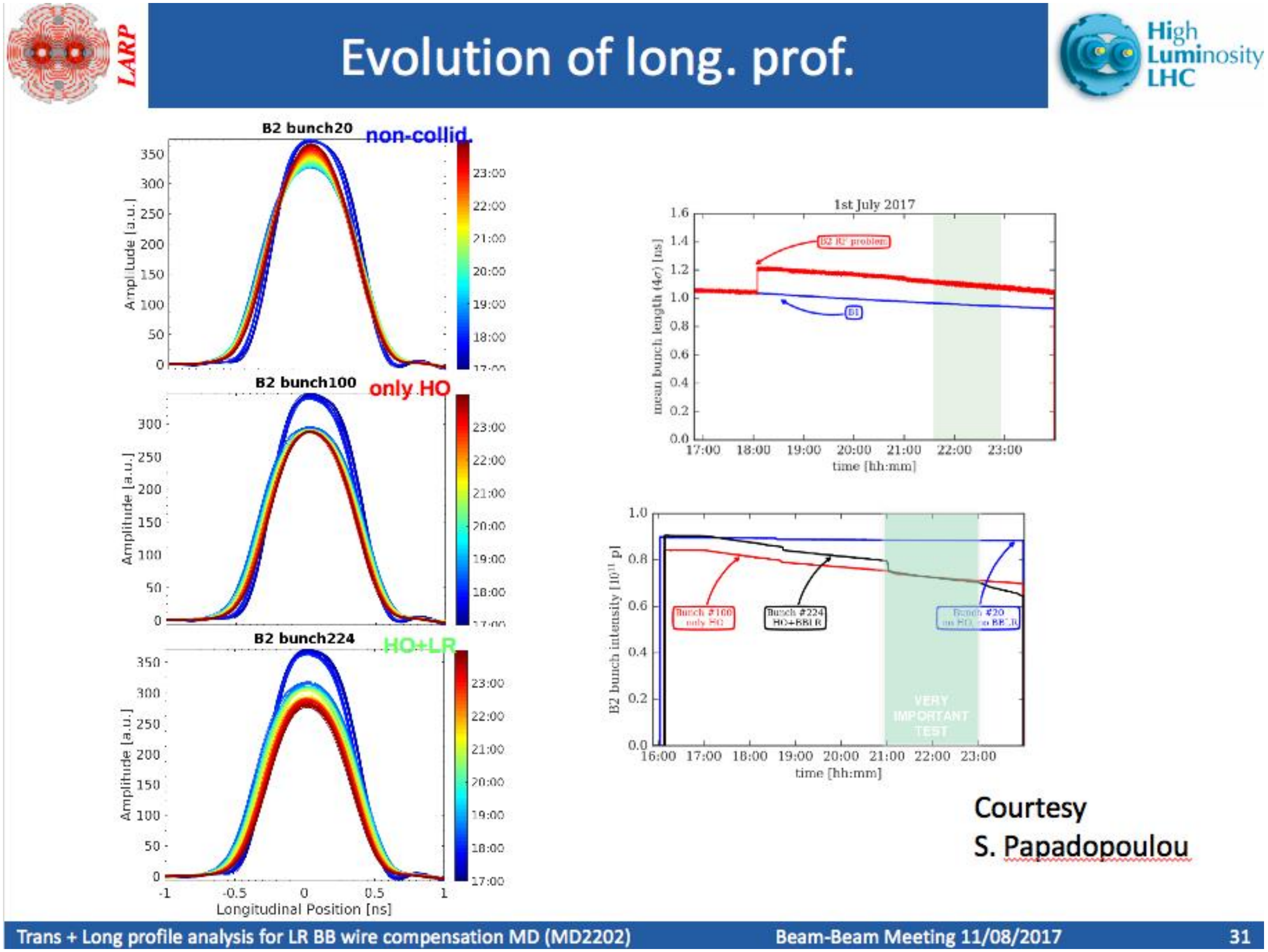
- It depends of the gain/settings of the CO feedback. With nominal FT settings is of the order of ~1 minute.



BBCW impact of the beam profiles (I)

- A very detailed presentation by Miriam and Stefania at https://indico.cern.ch/event/658908/

Longitudinal profiles



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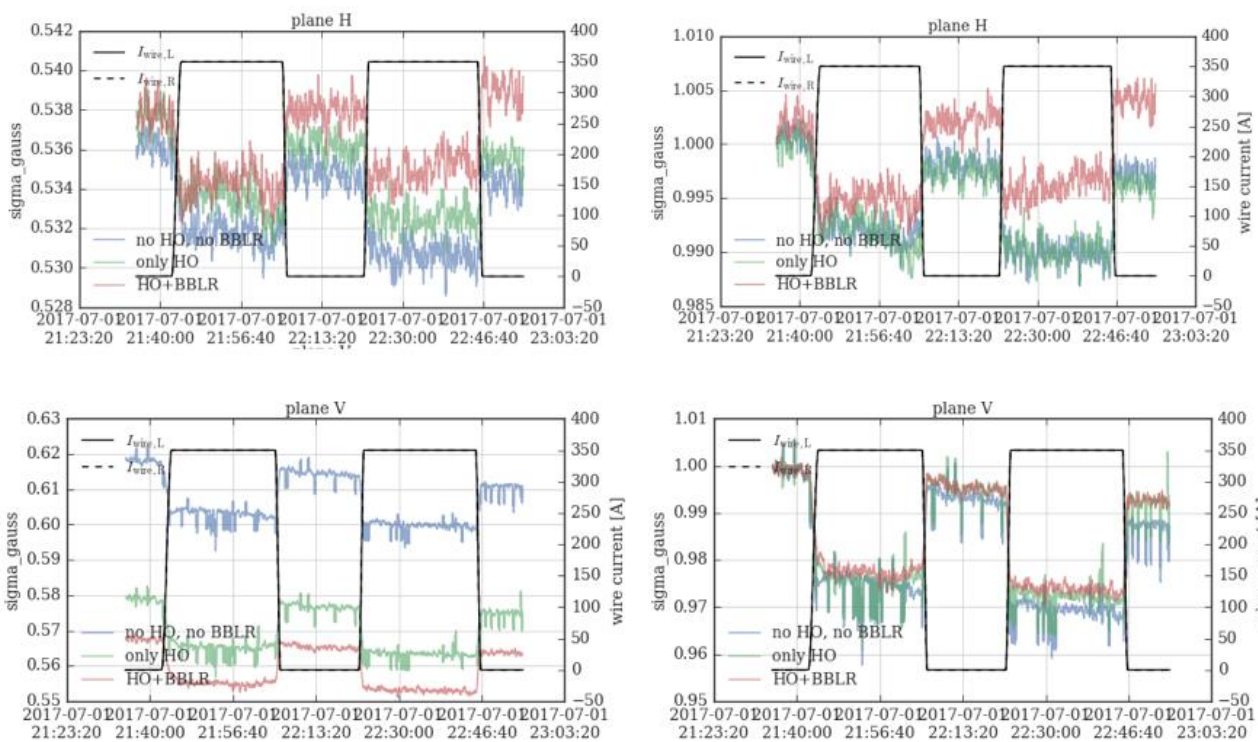
BBCW impact of the beam profiles (II)

- A very detailed presentation by Miriam and Stefania at https://indico.cern.ch/event/658908/

Transverse profiles

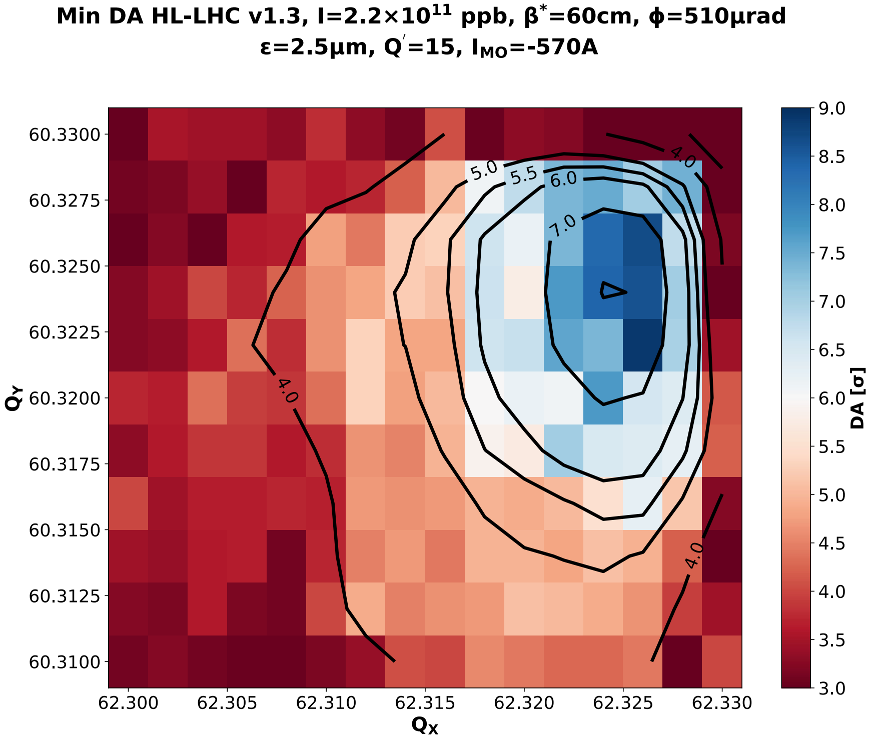
wire on-off – Gauss



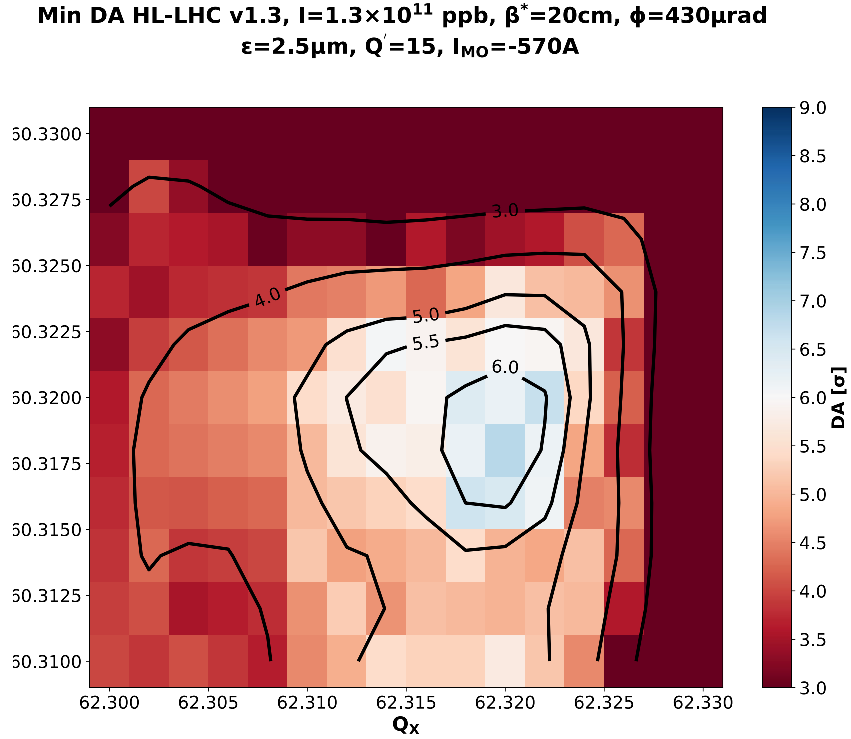
Beam size change is consistent with beta-beat (decrease of beta) + the profile changes observed

HL1.3 Tune Optimisation

Beginning of fill



End of Levelling



N. Karastathis